High Energy Gamma Rays and Neutrinos from Gamma Ray Bursts

Chuck Dermer (Naval Research Laboratory)

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Collaborators:
Armen Atoyan (Universite de Montreal)
Markus Böttcher (Rice University)
James Chiang (SLAC)
Kurt Mitman (UVA, Cambridge)

Gamma Rays and Neutrinos from Gamma Ray Bursts

Gamma Ray Burst puzzle is far from solved

(Long Duration) GRBs Linked to Massive Stars

SN 1998bw/GRB 980425

X-ray Lines and Features in 5-6 GRBs

Supernova-Like Reddened Excesses in ~5 Optical Afterglow

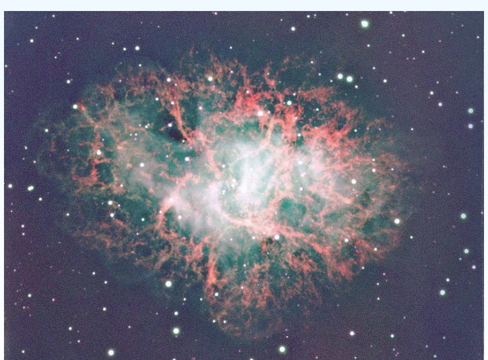
Standard Energy Reservoir Result ?

Supranova Model

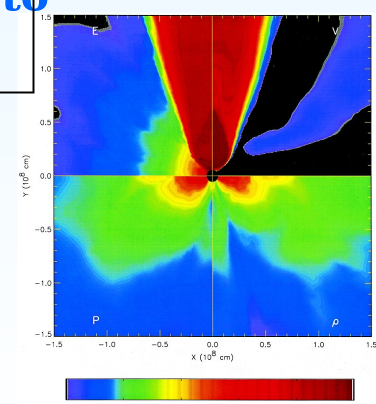
Two-step collapse to Black Hole

Collapsar Model

Direct collapse to Black Hole



External or Internal Shock Model for Prompt GRB Emission



Gamma Ray Bursts: Basic Facts (Long Duration GRBS)

Redshift Distribution:

0.17 (GRB 030329) < z < 4

Mean Redshift at z ≈ 1

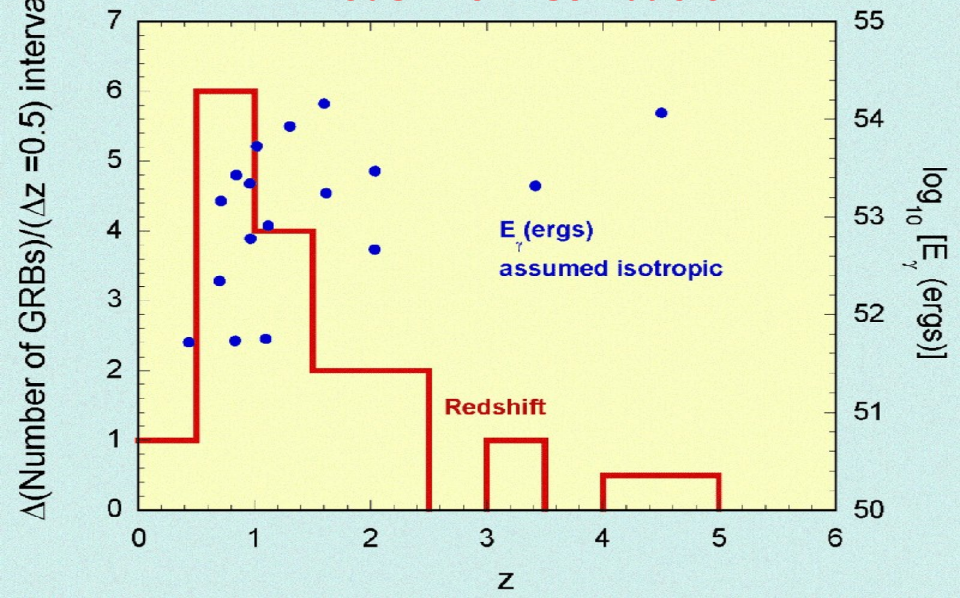
$d_L \approx 2 \cdot 10^{28}$ cm

Fluence and Energy:

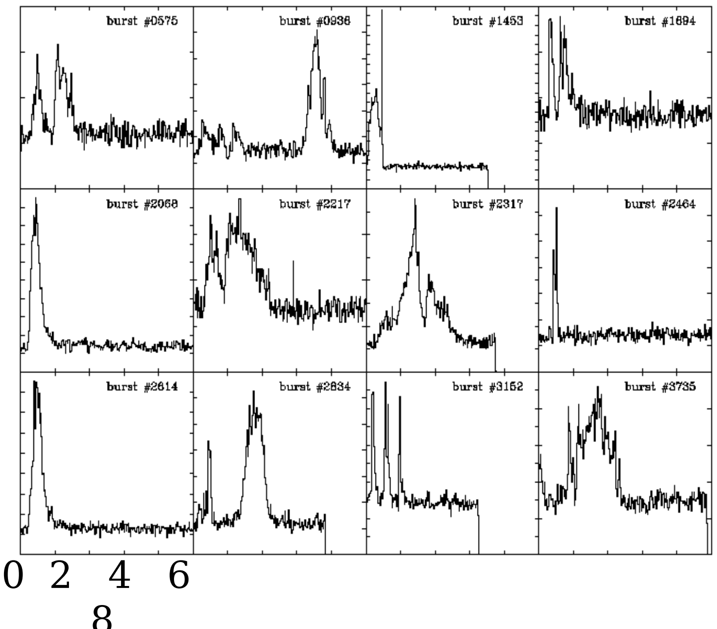
Typical Fluences: 10^{-6} - 10^{-4} e

$\Rightarrow E_\gamma \approx 10^{51}$ - 10^{54} ergs

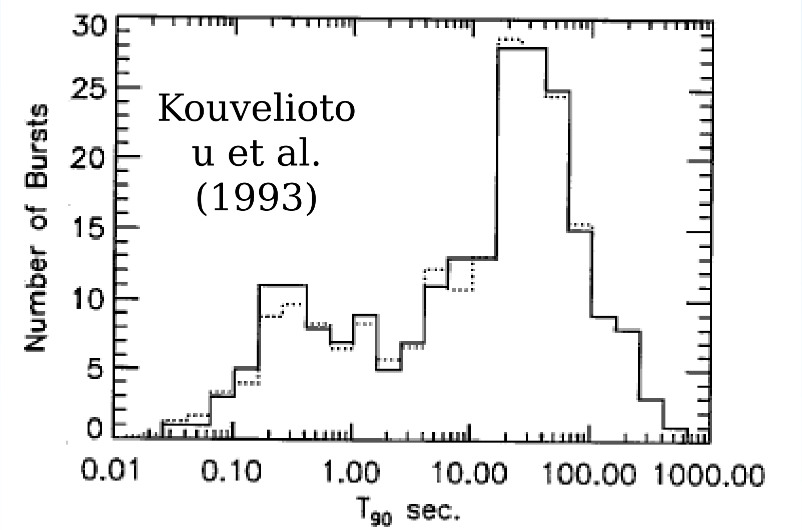
Durations: 2-500 s



Sample of Different GRB Light Curves

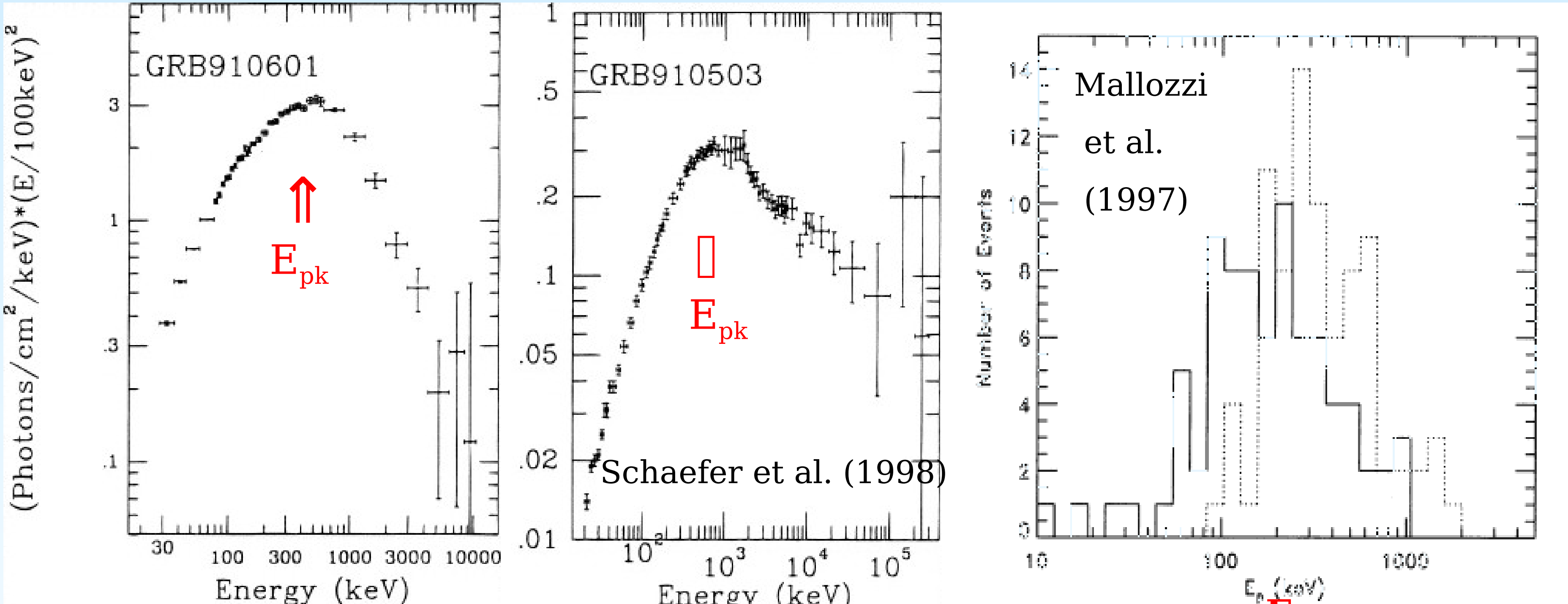


Duration Distribution



BATSE GRBs: Spectra and Peak Energy Distributions

E_{pk} = Peak energy of νF_ν Distribution



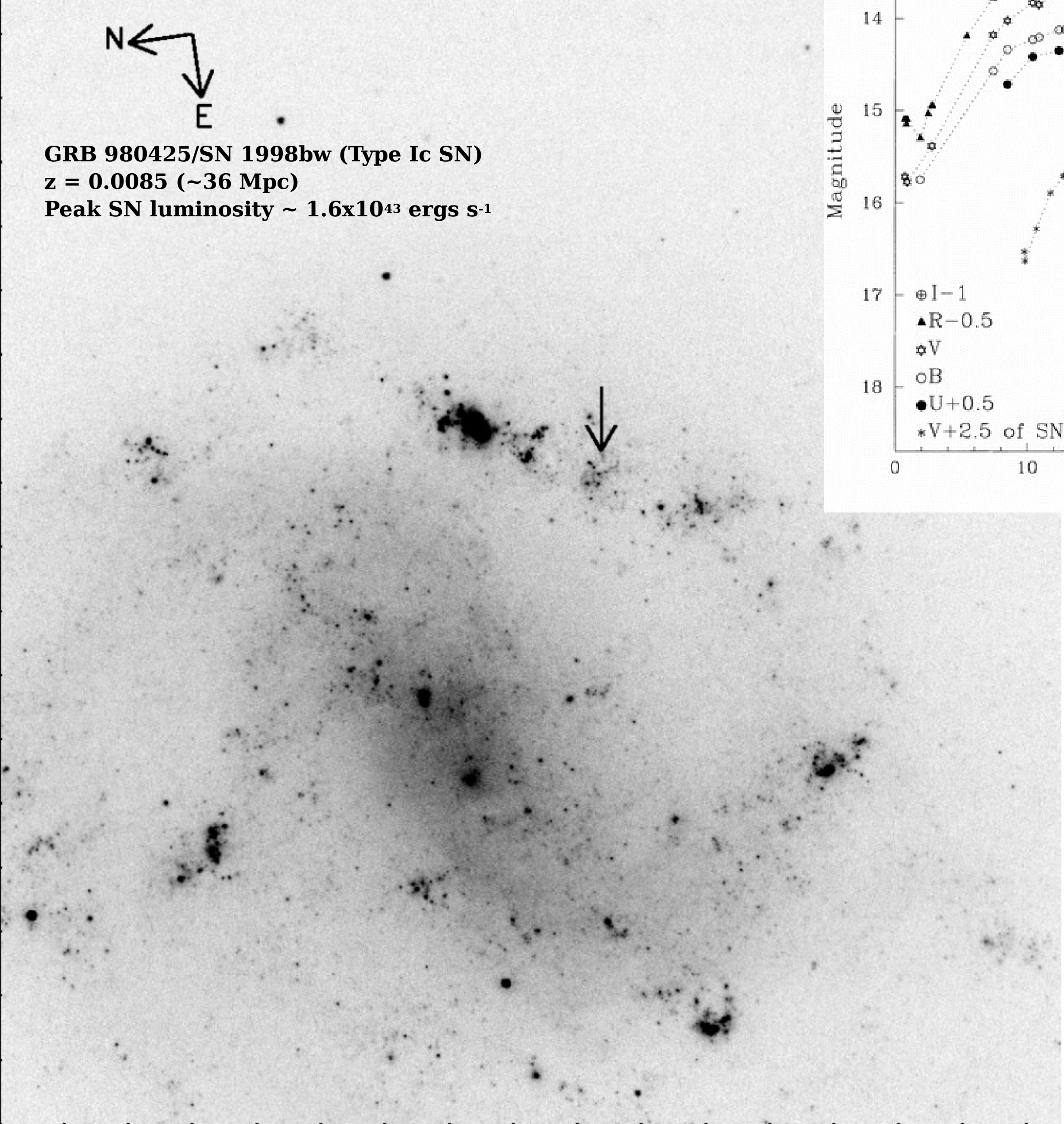
Spectra

E_{pk} Distribution

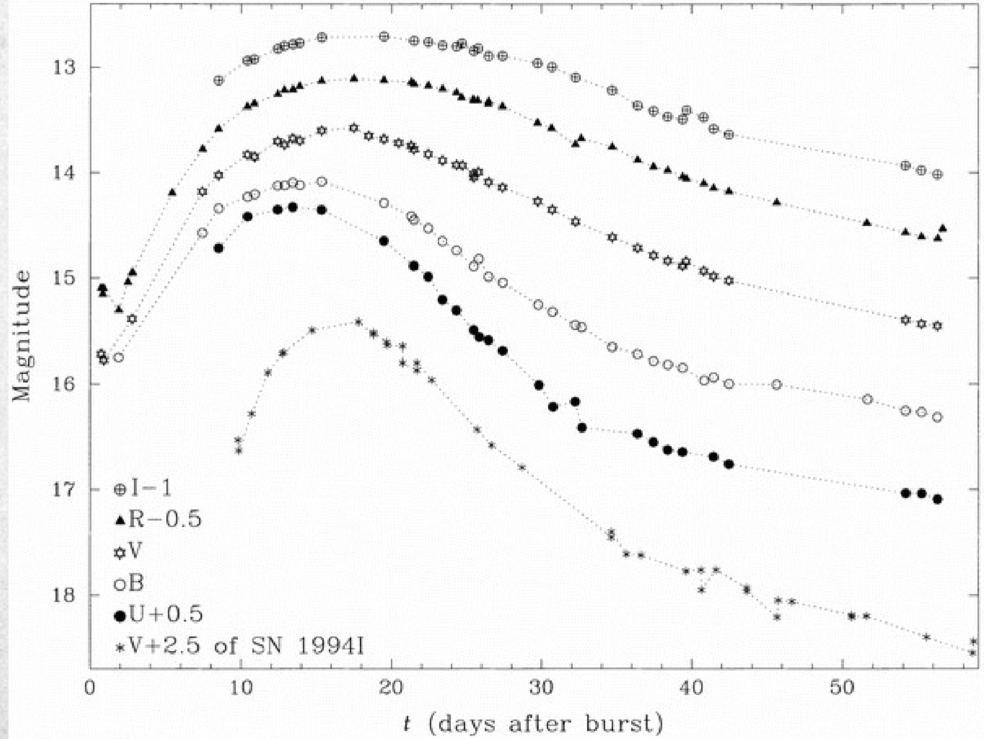
BATSE GRBs Trigger Criteria:

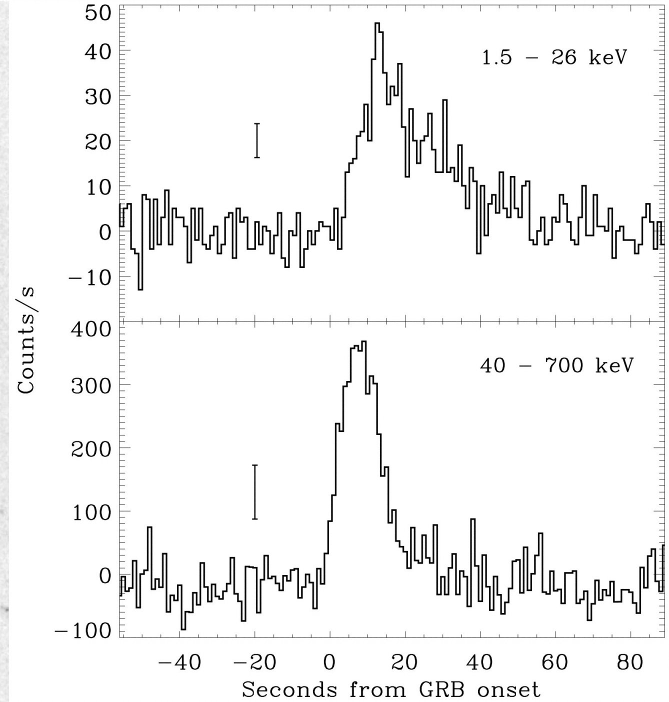
Triggers on 5.5 σ excess over background in two detec
in 50-300 keV range in 64 ms, 256 ms, 1.024 s time sc

GRB-Supernova Connection



GRB 980425/SN 1998bw (Type Ic SN)
z = 0.0085 (~36 Mpc)
Peak SN luminosity ~ 1.6×10^{43} ergs s^{-1}





Fireball/Blast Wave Model for GRBs

Meszaros and Rees, Paczynski, Piran…

Observations: **Large energy releases, large powers, short time variabi**

Explanation: **Deposit energy E in compact region to form pair fireball**

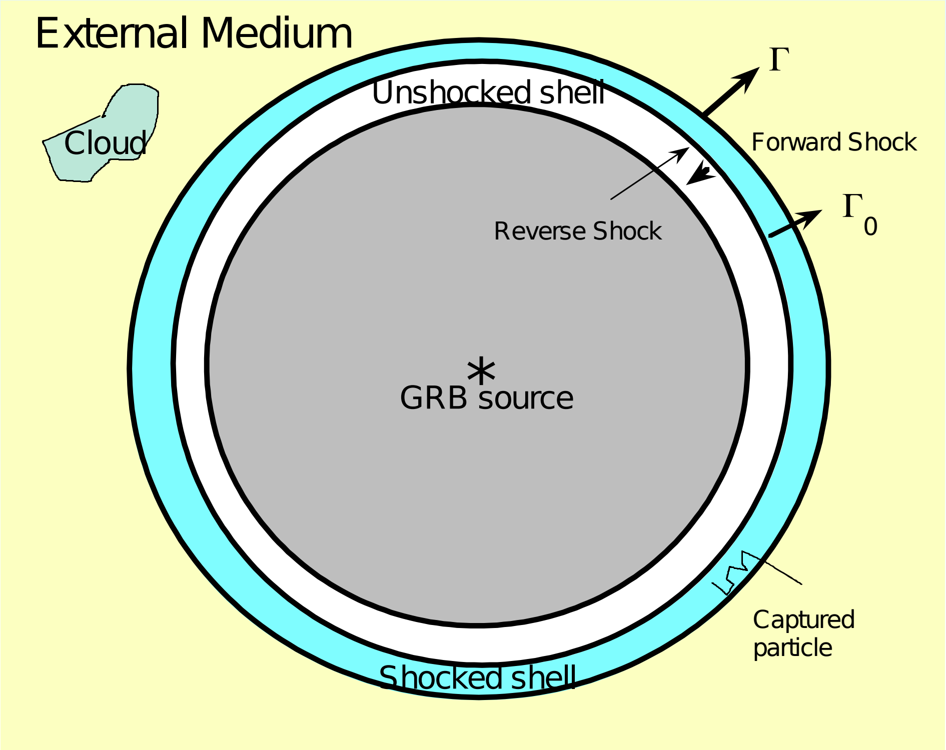
Result: **Fireball adiabatically expands and reaches coasting velocity determined by baryon-loading M_b**

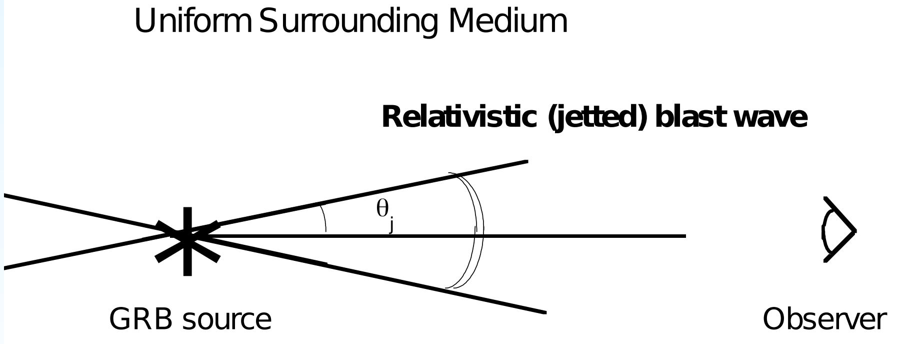
Coasting (initial) Lorentz factor: $\Gamma_0 = E/M_b c^2$

Capture particle from surroundings: **Directed kinetic energy → intern**

Bulk of swept-up energy in hadrons (if surrounding medium is not pa

Blast wave decelerates and radiates on deceleration timescale t_d



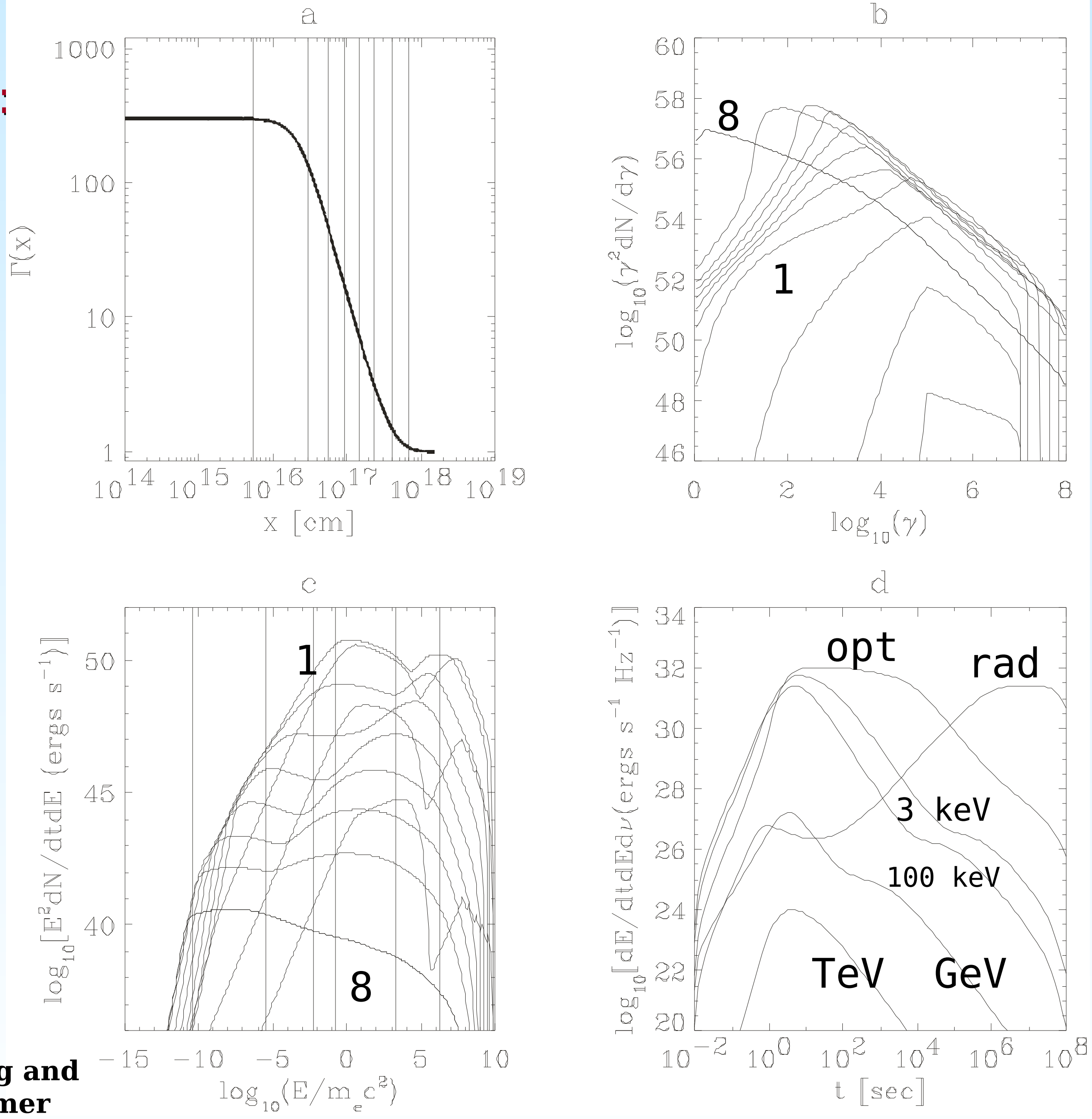


Numerical Simulation: Uniform Surrounding Medium

- Dominant synchrotron radiation at MeV energies
- Two peaks in νF_ν distribution
- Generic rise in intensity until t_{dec}, followed by constant or decreasing flux (except in self-absorbed regime)
- Strong SSC component for this parameter set

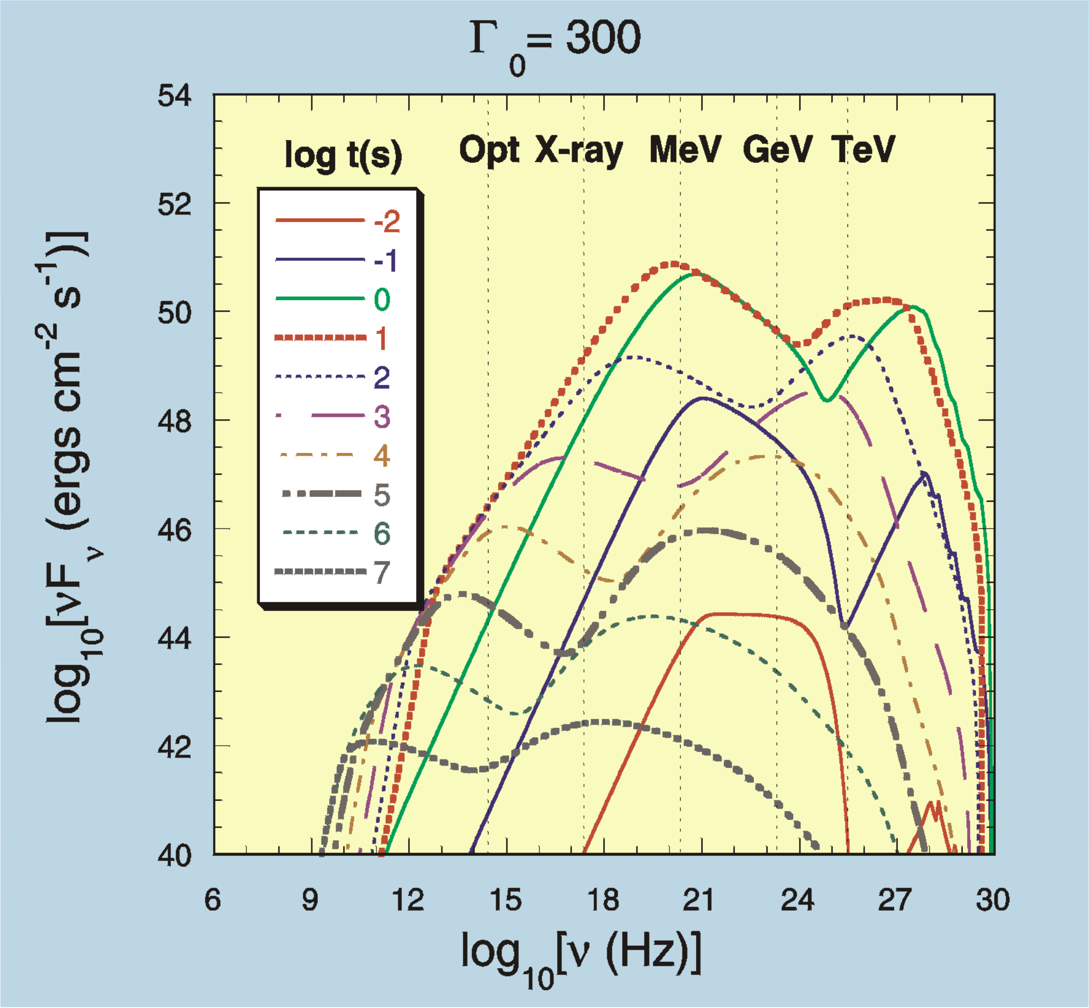
$E = 10^{54}$ ergs

$n_0 = 100$ cm^{-3}



Chiang and Dermer (1999)

Numerical Simulation Model of GRB Radiation



$E=10^{54}$ ergs

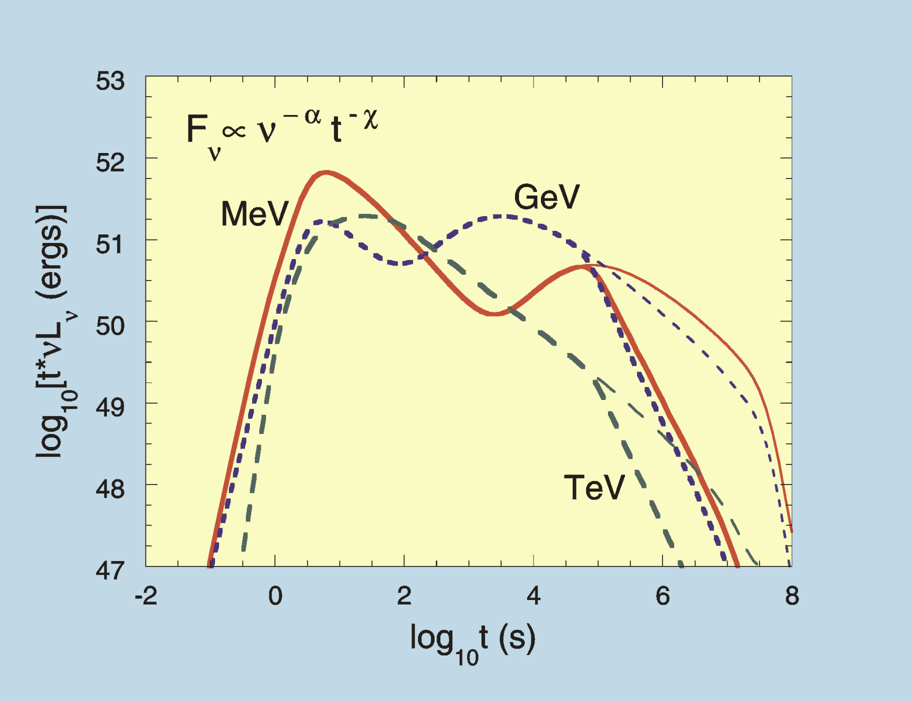
$n_0=100$ cm^{-3}

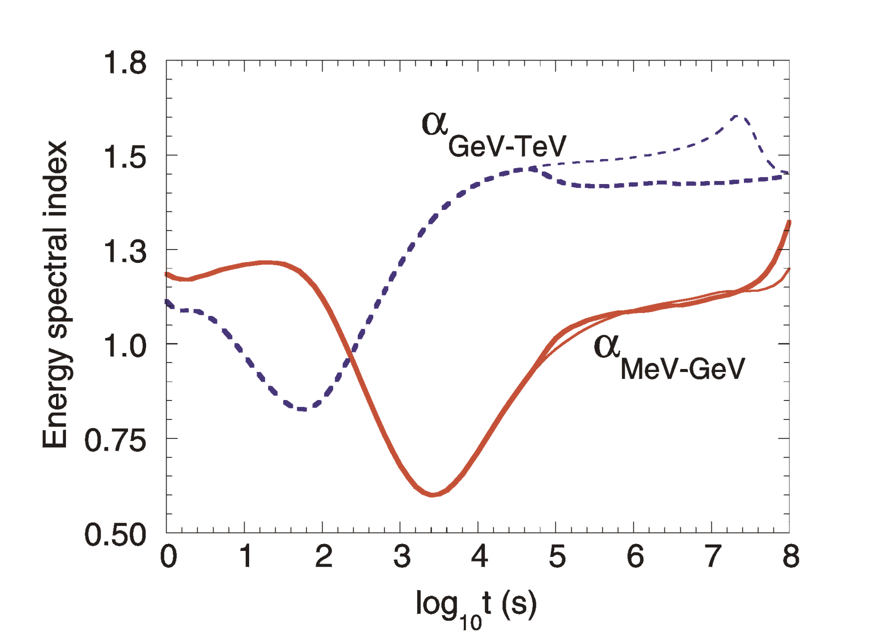
- νF_ν spectra shown at observer times 10^i seconds after GRB event

Gamma Ray Light Curves

SSC component introduces a delayed hardening in **MeV** light curves several orders of magnitude below the flux of the prompt emission

Onset of SSC hardening at MeV energies occurs at t ≈ 10^3 s.

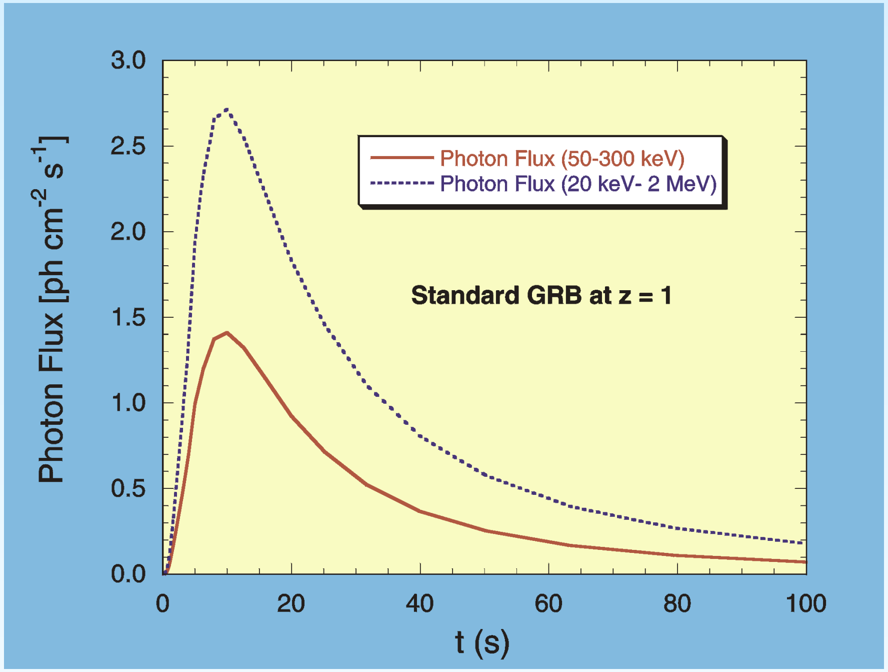




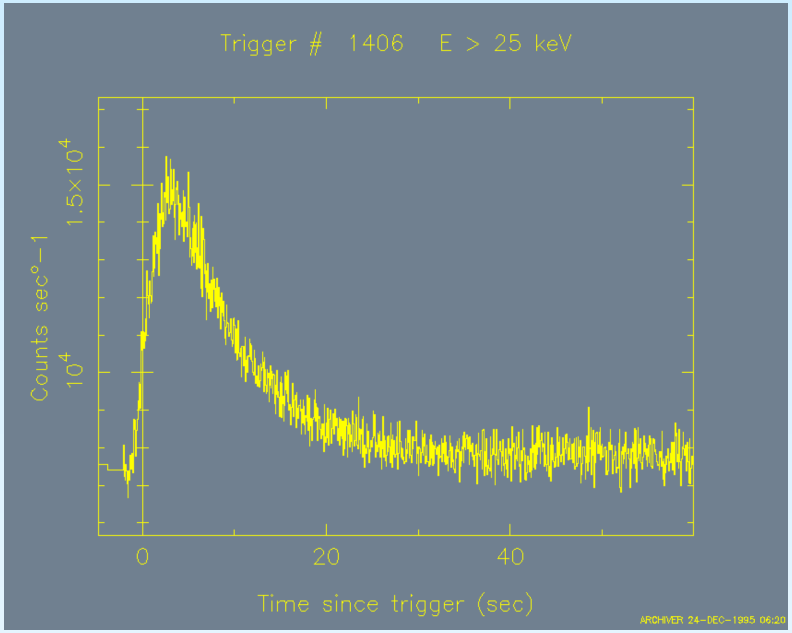
TeV component roughly coincident in time with prompt MeV radiation

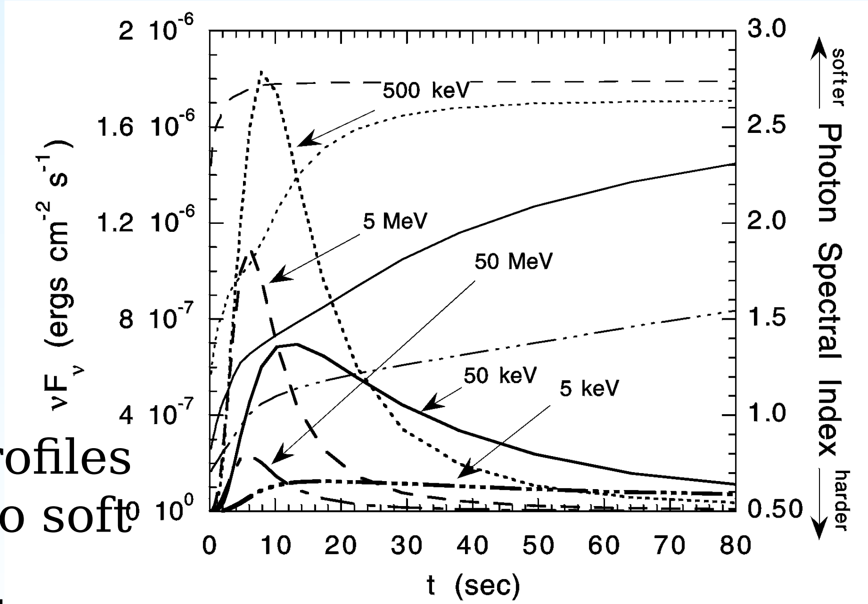
Additional radiation processes (external Compton, hadronic) can make stronger GeV-TeV emission

Most common prompt GRB light curve



Dermer, Böttcher, and Chiang (2000)





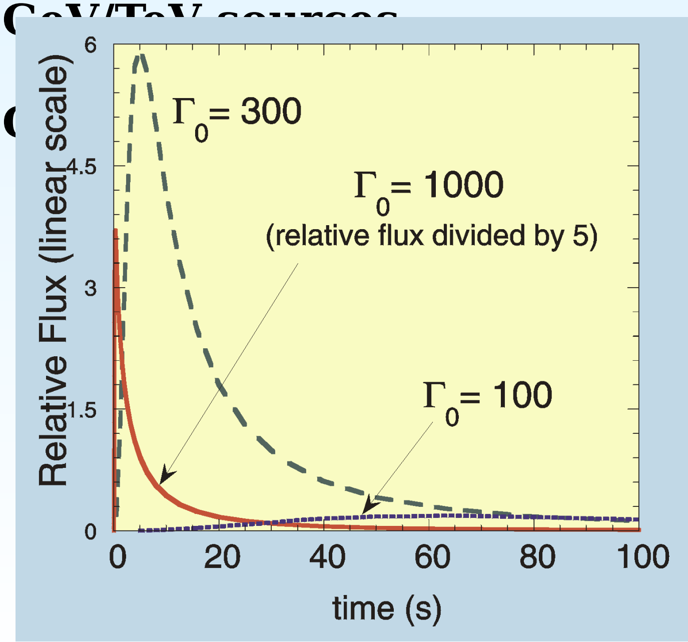
- Reproduces behavior of FRED-type profiles
- Hardness-intensity correlation, hard to soft evolution
- ⇒Smooth profile GRBs due to external shock

Dirty and Clean Fireballs: strong GeV/TeV sources

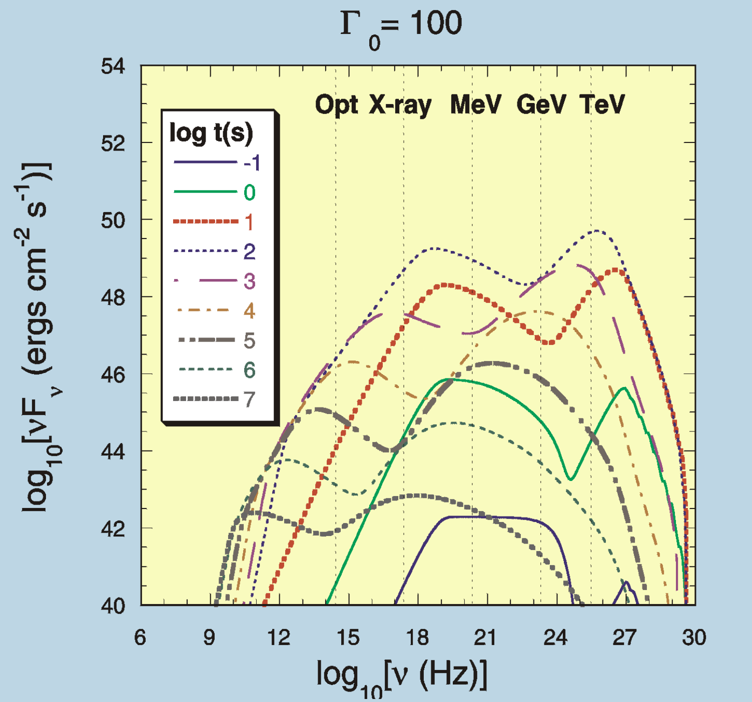
Observed properties most sensitive to initial Lorentz factor of outflow (or baryon loading)

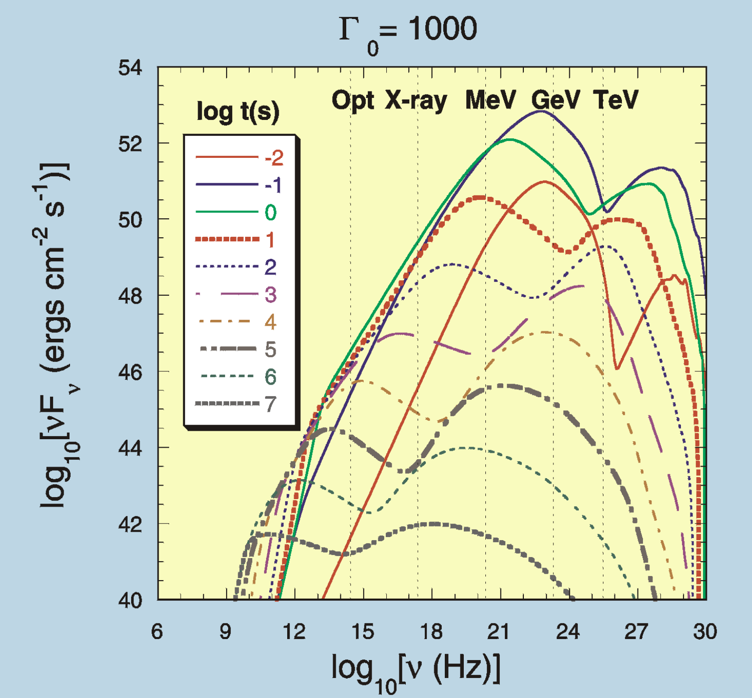
Instrumental selection biases against detecting fireballs with $\Gamma_0 << 100$ and $\Gamma_0 >> 1000$

X-Ray Flashes (or X-ray rich GRBs) = Dirty Fireballs; Untriggered GeV/TeV sources

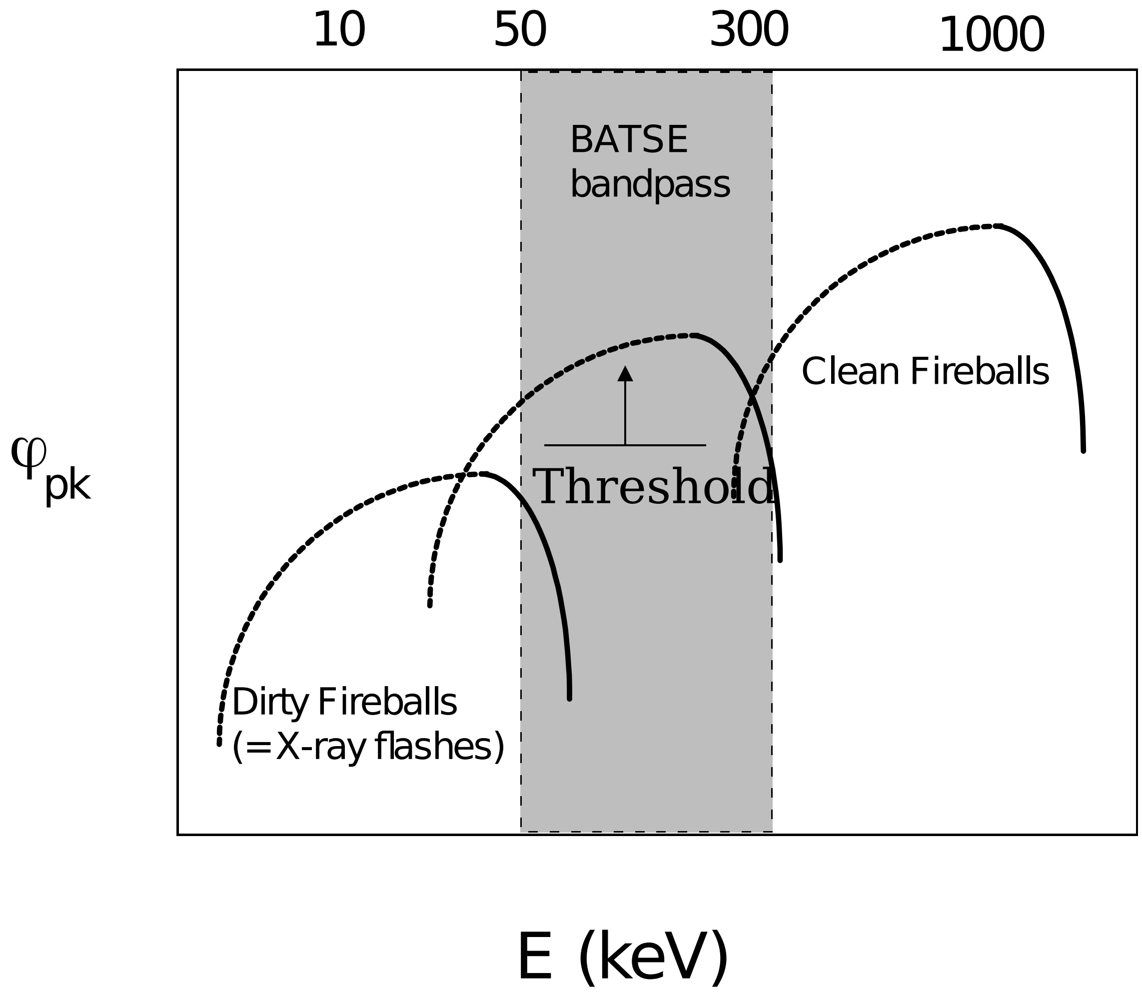


Dermer, Chiang, and Böttcher (2000)





E_{pk} Distribution Explained

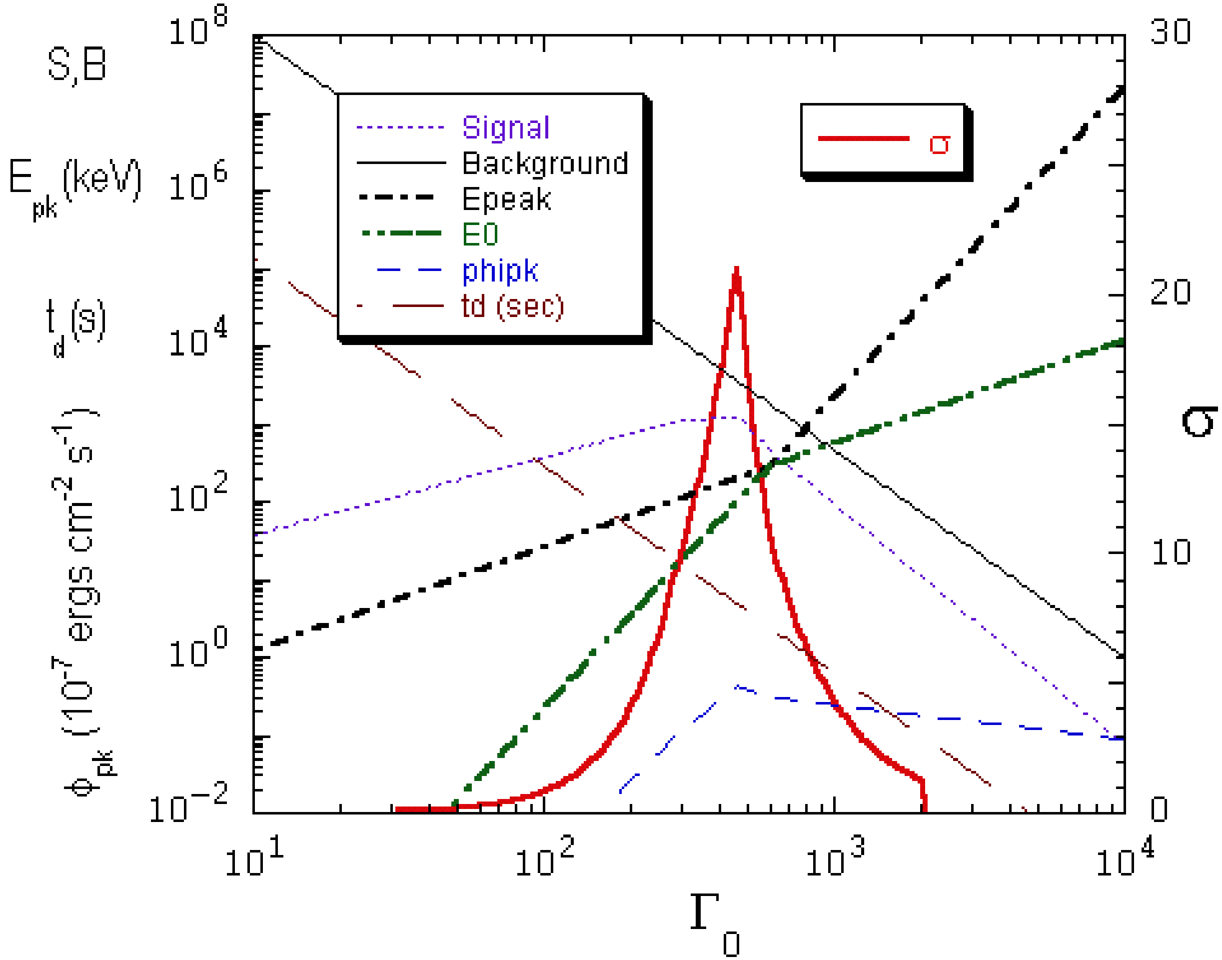


Detection Sensitivity to GRBs (Fireball Transients)

BATSE Triggering in 50-300 keV Range:

Most sensitive when $E_{pk} \approx 100$ keV

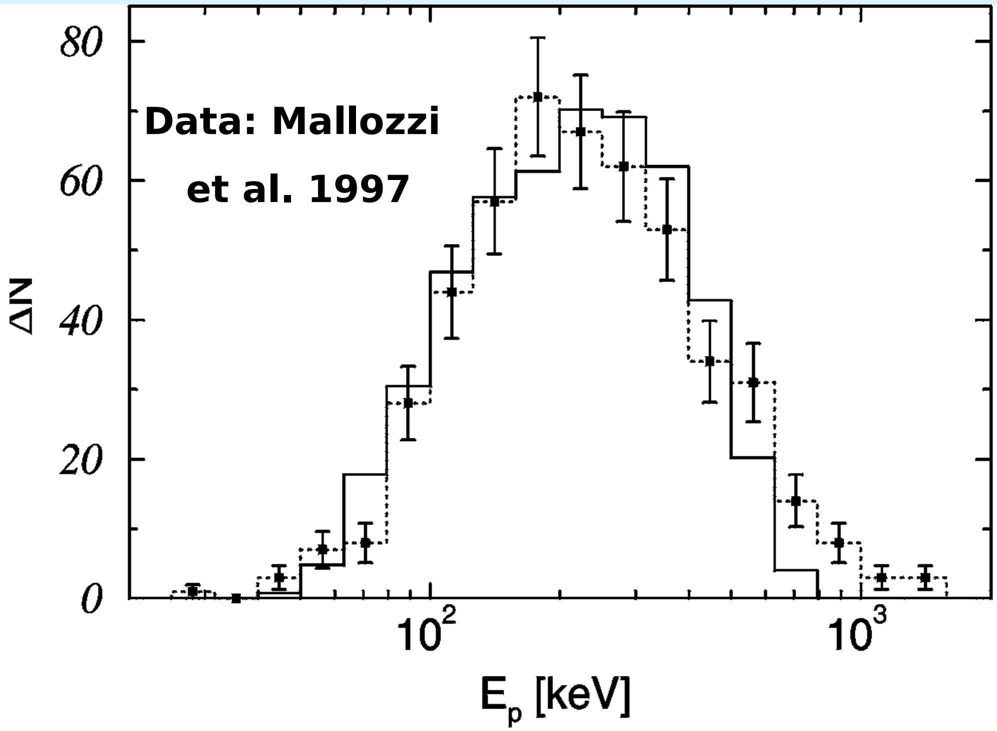
$$\sigma = \frac{S}{\sqrt{B}}$$



Use Spectral Characterization of Sari, Piran and Narayan (1998)

Explain E_{pk} Distribution

Broad (power-law) distribution of baryon-loading Γ_0 (no fine tuning)



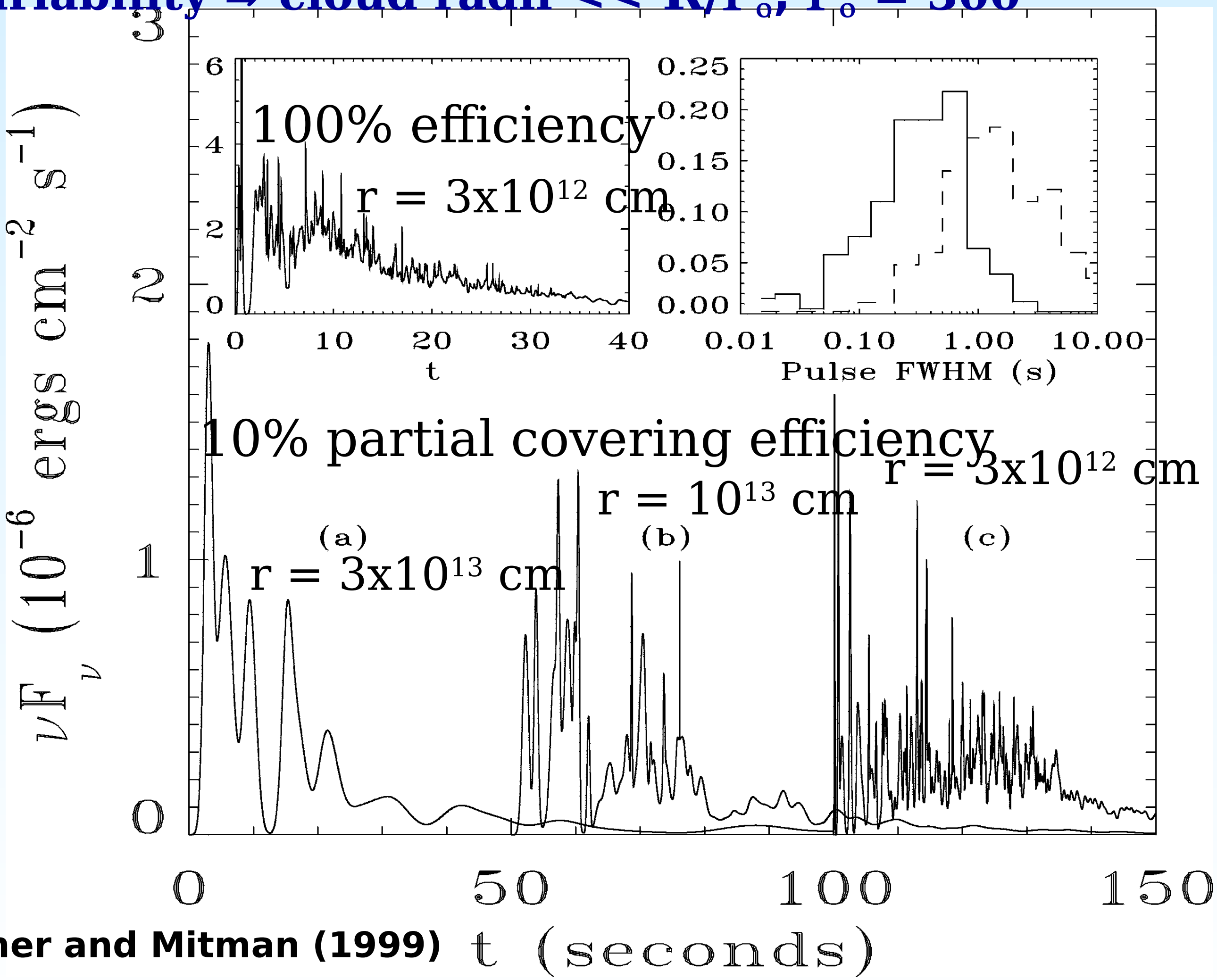
Böttcher & Dermer (ApJ, 2000, 529, 635)

635)

Short Timescale Variability due to Inhomogeneities in Surrounding Medium

Clouds with thick columns (>4x10^{18} cm^{-2}) Total cloud mass still small (>~10^{-4} M$_o$)

Variability ⇒ cloud radii << R/Γ$_o$, Γ$_o$ = 300



Requires highly clumpy medium at 10^{16} – 10^{17} cm

Cloud sizes ≈ 10^{12} –10 ^{13} cm to agree with pulse paradigm (Norris et al. 1996)

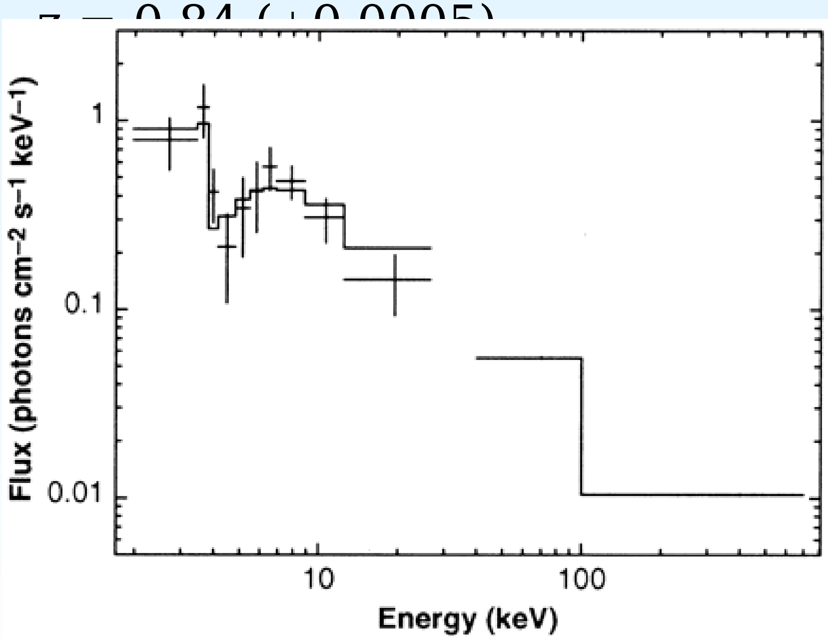
Good efficiency (compared to internal shocks)

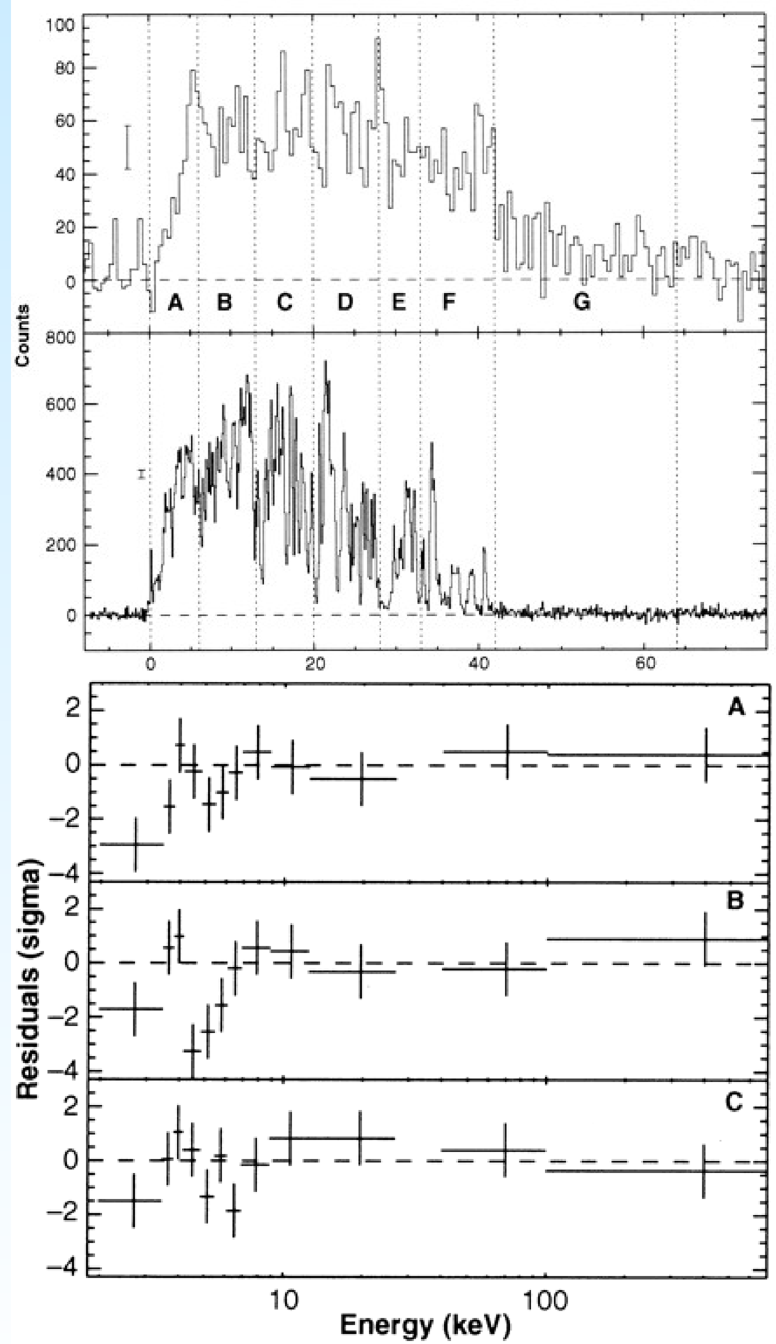
Dermer and Mitman (1999)

GRB 990705: Observations

- Observation of absorption edge at ~ 3.8 keV during the prompt phase (Amati et al. 2000) in intervals A and B
- Photoelectric absorption at Fe K-edge ⇒z = 0.86 (±0.17)

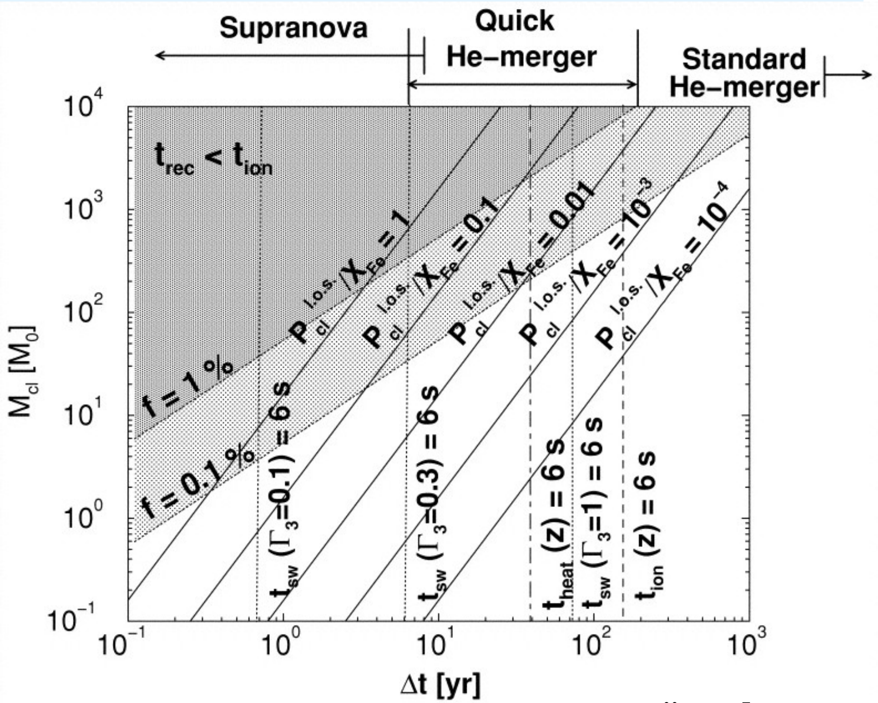
z = 0.84 (±0.0005)

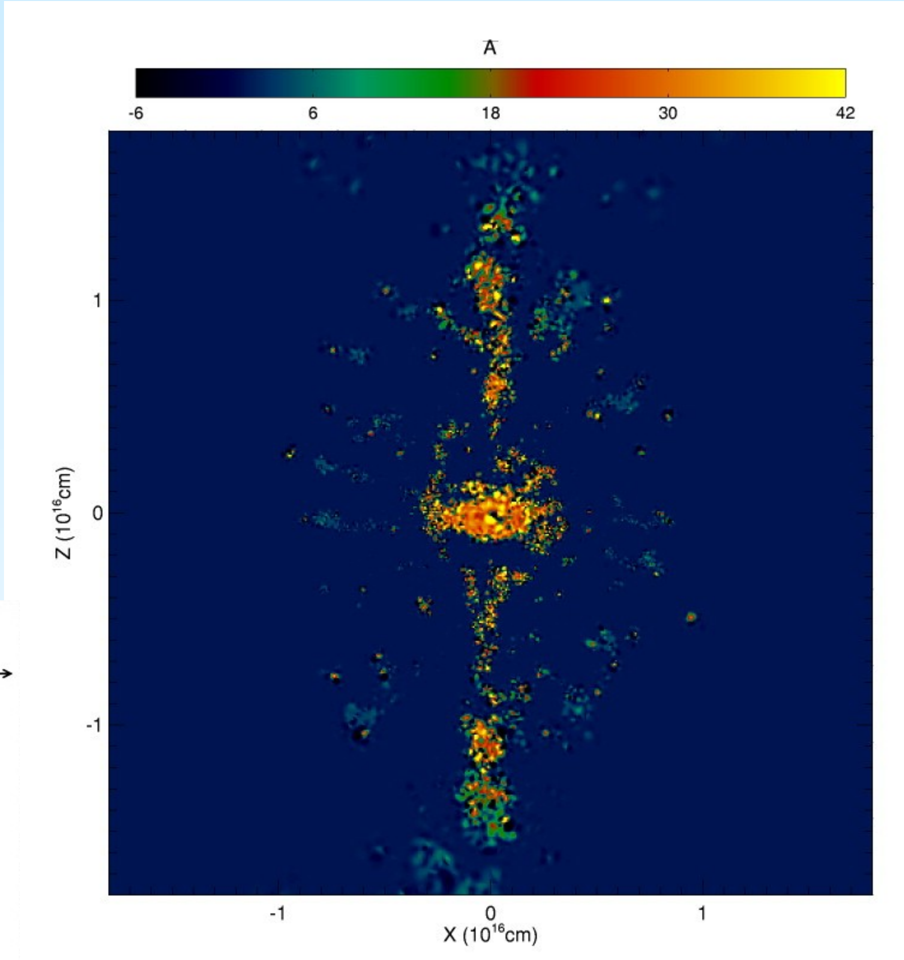




GRB 990705: Interpretation

Can be explained with strong Fe enhancements; large amount of Fe within 1 pc; strong clumping of ejecta





Size scale of clumps ~< 10^{13} cm

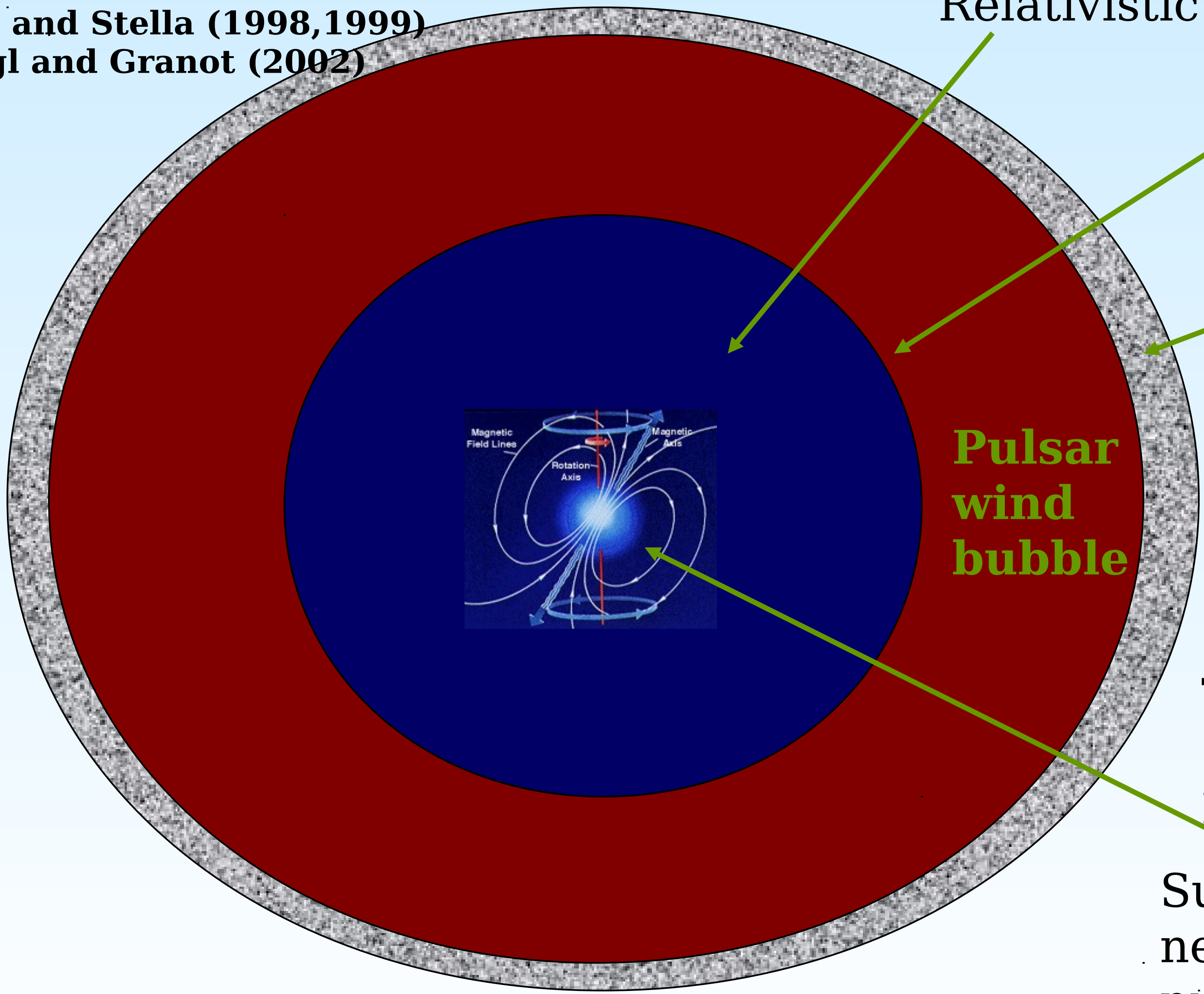
Density >~ 10^{10} cm^{-3}

Probability of observing absorption in He-merger/collapsar model << 1%

Böttcher, Fryer and Dermer (2002)

Source Model: Supranova Model

Vietri and Stella (1998,1999)
Königl and Granot (2002)



Relativistic cold MHD wi

MHD shock/ nonthermal particle acceleration

SNR shell

Two-step collapse to black hole

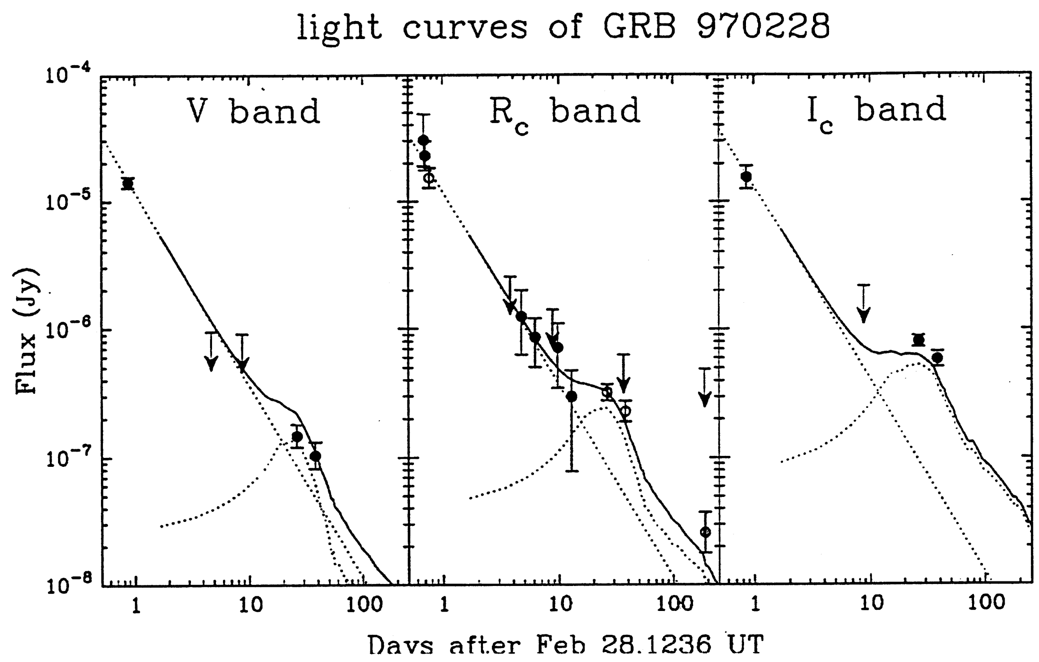
Explains X-ray features

Supramassive neutron star/ pulsar

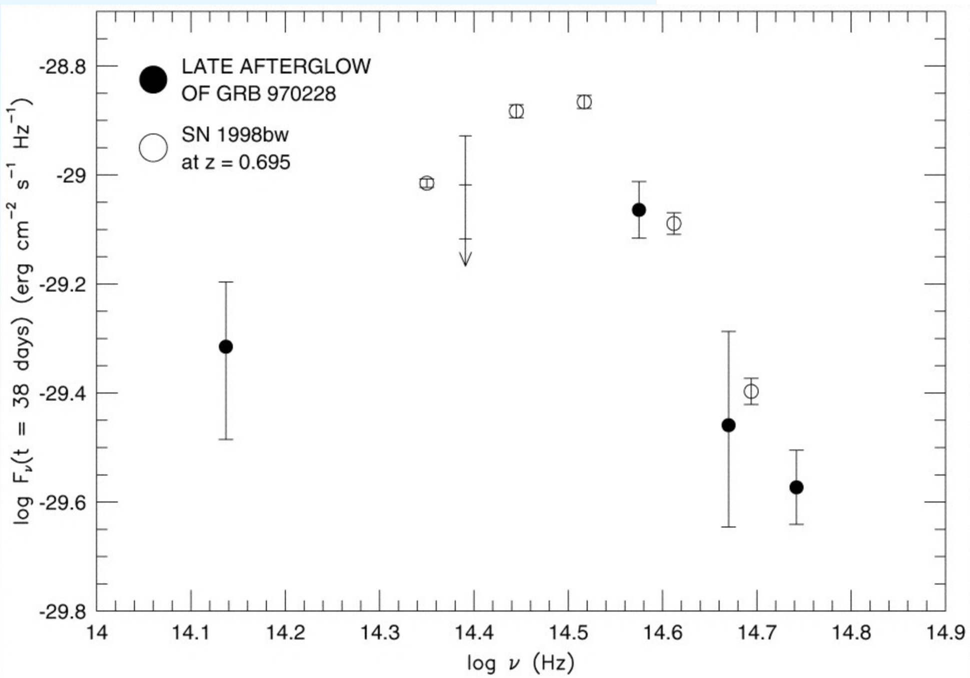
Shell expands due to pressure of wind

Delayed Red Bump (Supernova Signature) in GRB 970228

- $z = 0.695$
- **Diversity of light curves of Type Ic SNe**
- $(1+z)\, t_{max} \cong 30$ **days**

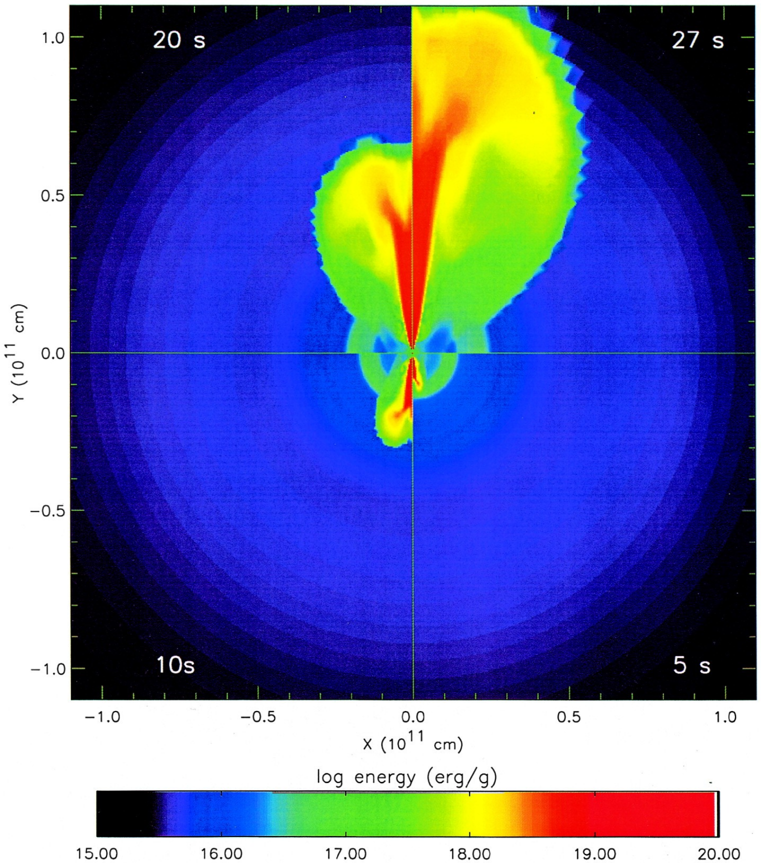


Galama et al. (1999)

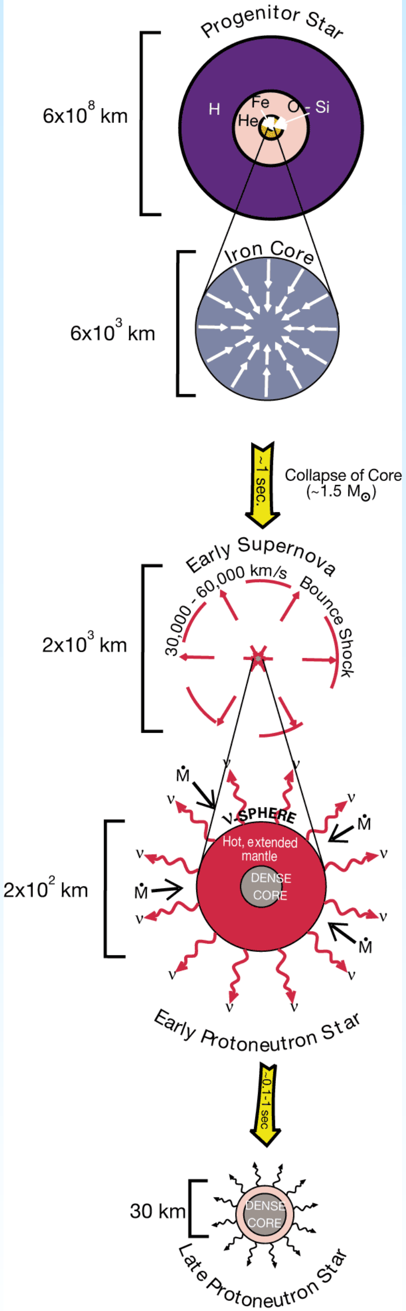


Source Model: Hypernova/ Collapsar Model

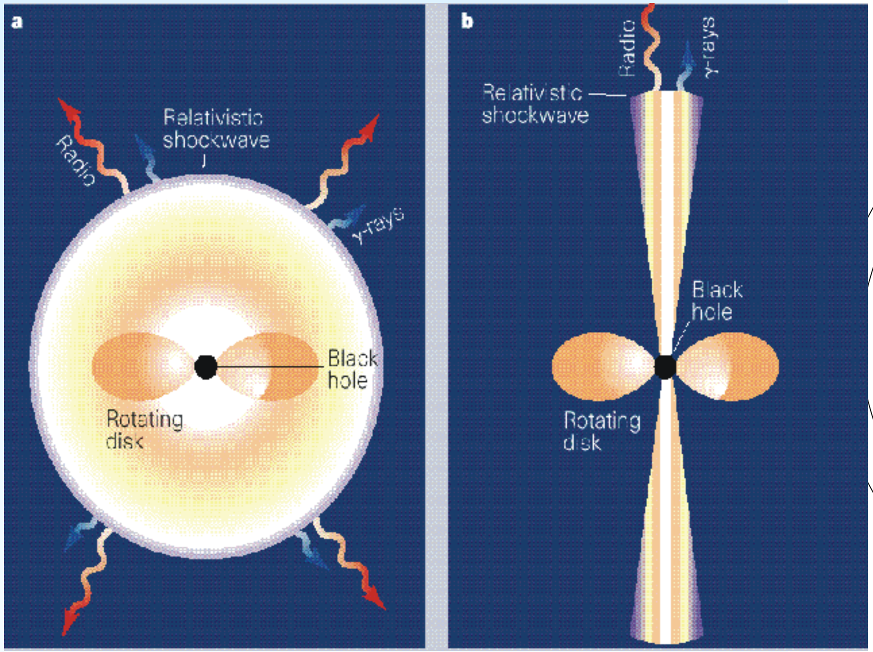
- Direct Collapse of Core to Black Hole
- Energy released at rotation axis
- Requires active central engine
- “Failed” Supernova
- Quenching of relativistic outflow

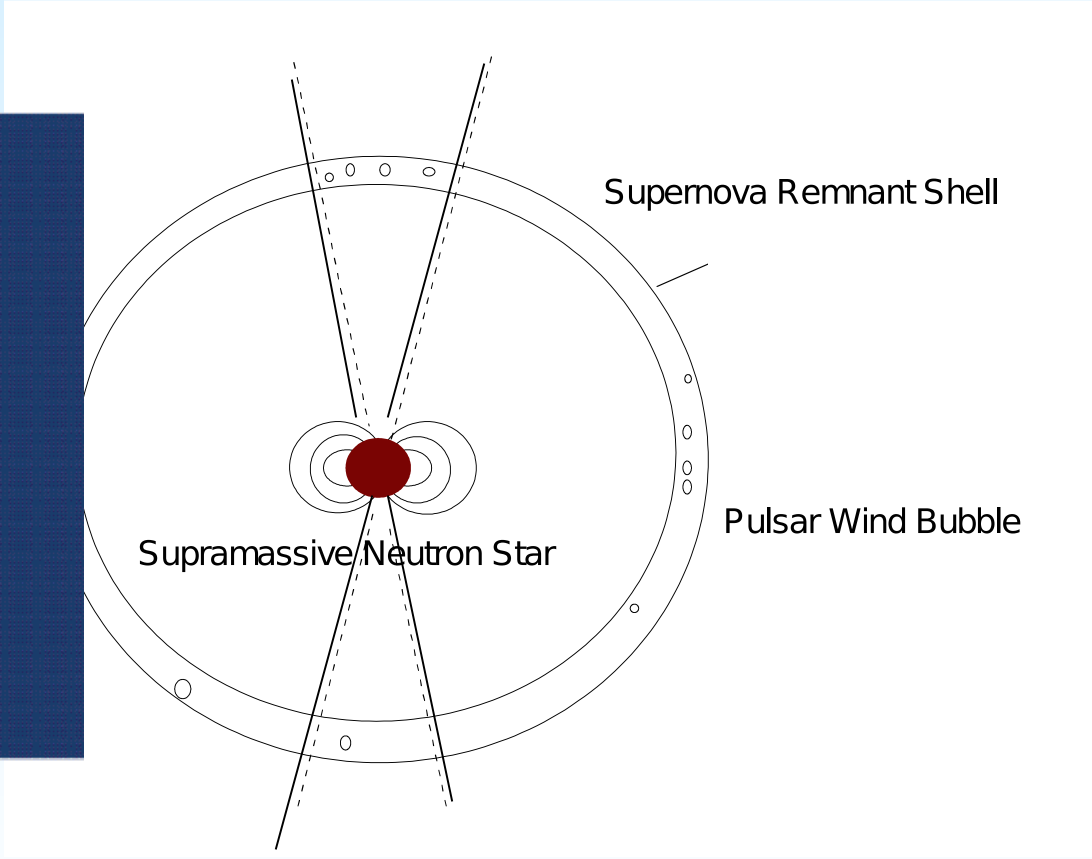


(MacFadyen, Woosley, and Heger 2001)



How to Test Collapsar and Supranova Models?





High-Energy Neutrinos from GRBs

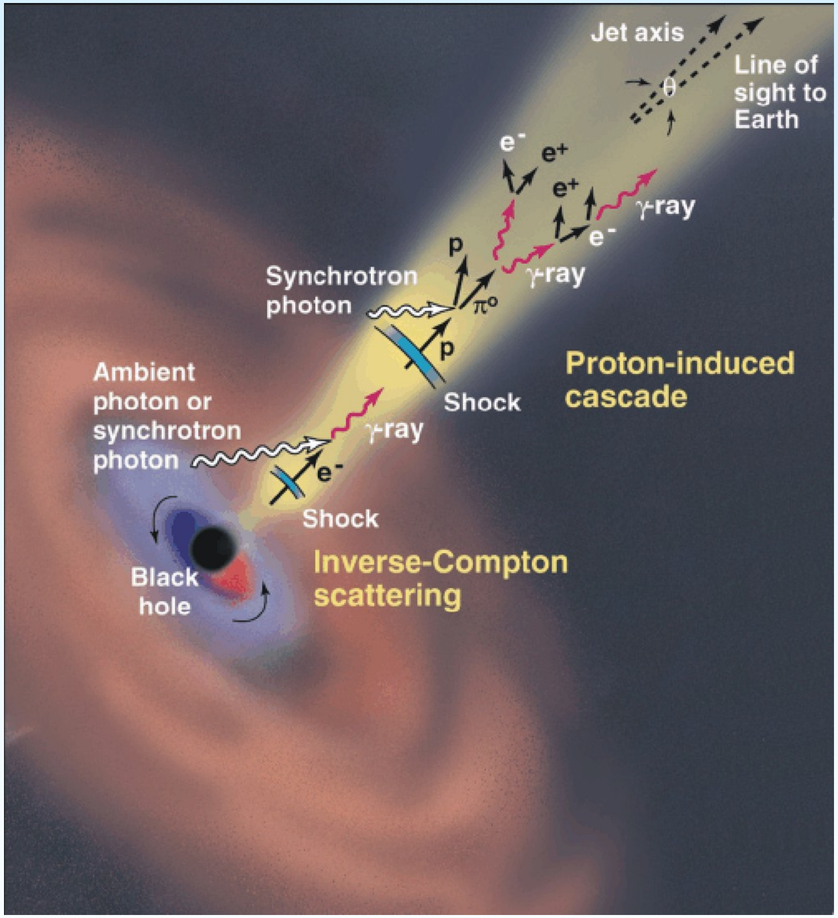
Nonthermal gamma-rays ⇒ nonthermal particles
+ Intense photon fields

⇒ Strong photomeson production

$$p + \gamma' \rightarrow n + \pi^{+}\ ,\ p + \pi^{0} \rightarrow \gamma$$

$$\pi^{+} \rightarrow e^{+} + \nu_{e} + \nu_{\mu} + \bar{\nu}_{\mu}$$

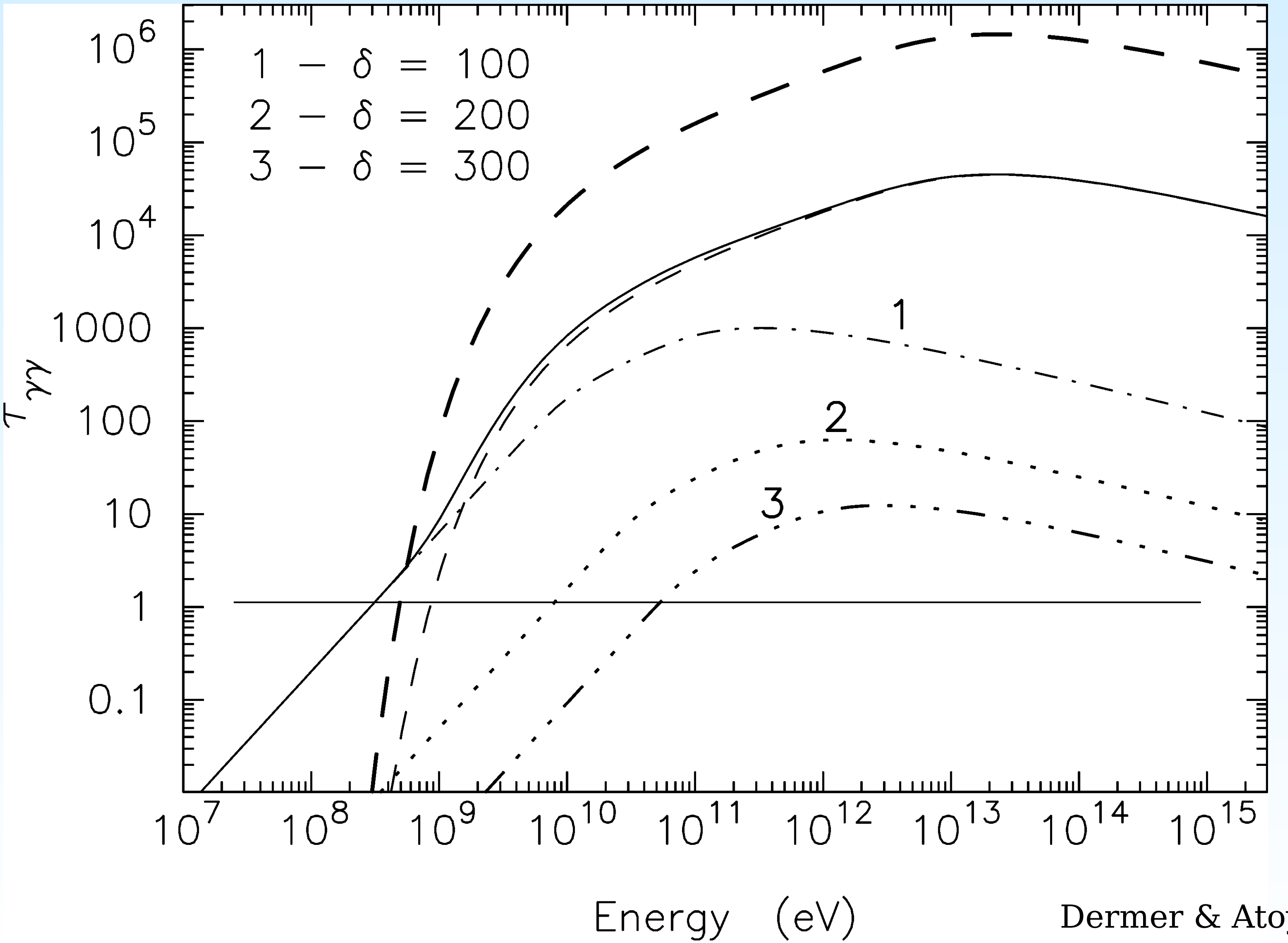
Very different radiation environments in collapsar and supranova models



Credit: J. Buckley

γγ Optical Depth

Photon attenuation strongly dependent on δ in collapsar model



$\tau_{\gamma\gamma}$ evolves in collapsar model due to evolving Doppler factor and internal radiation field

Dermer & Atoyan, 2003

Energy Fluence of Photomeson Muon Neutrinos

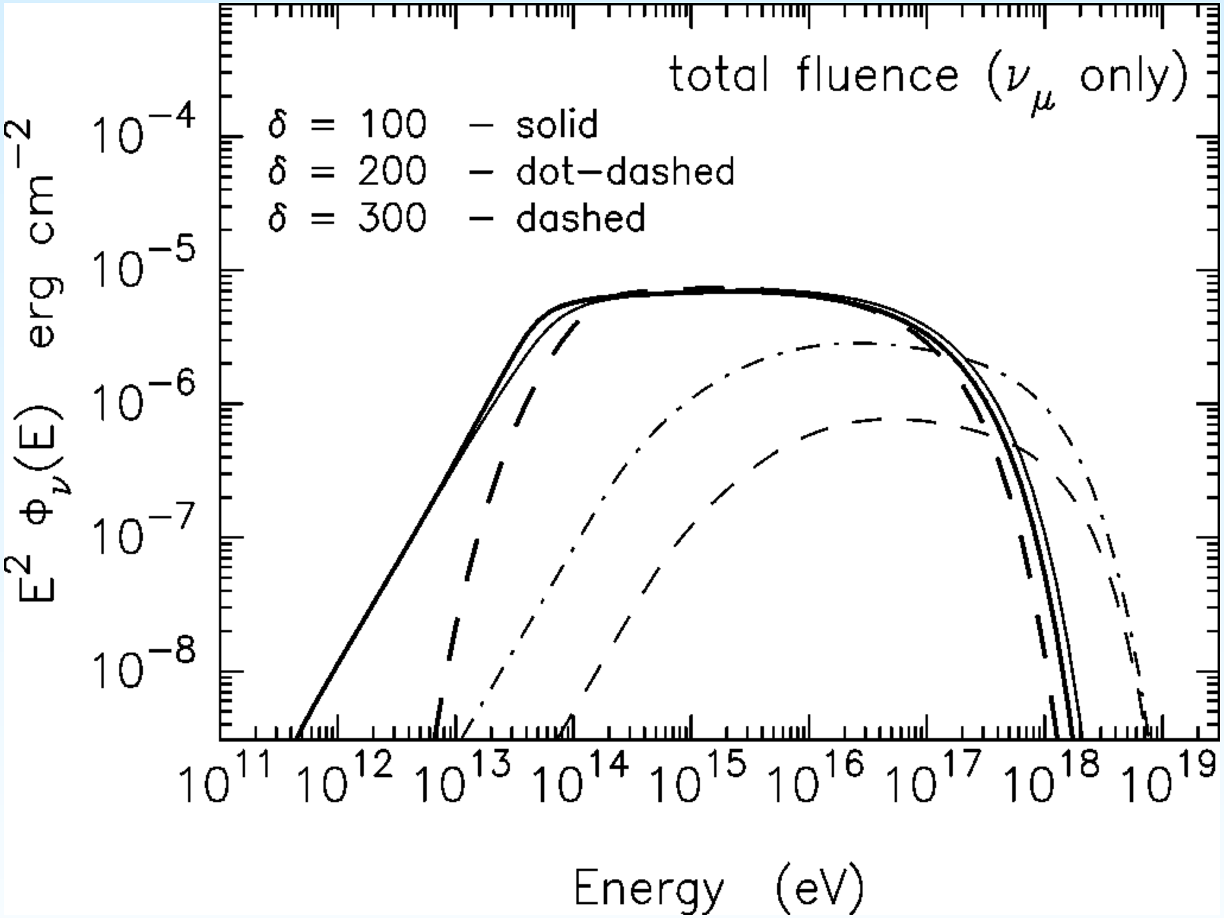
(Inject equal energy in protons as observed in photons)

For a fluence of 3x10^{-5} ergs/cm^2 (2-3 GRBs per month at this level)

N_ν predicted by IceCube:

$N_\nu \approx$ 0.0032, 0.00015, 0.00001 for δ = 100, 200, and 300, respectively in collapsar model

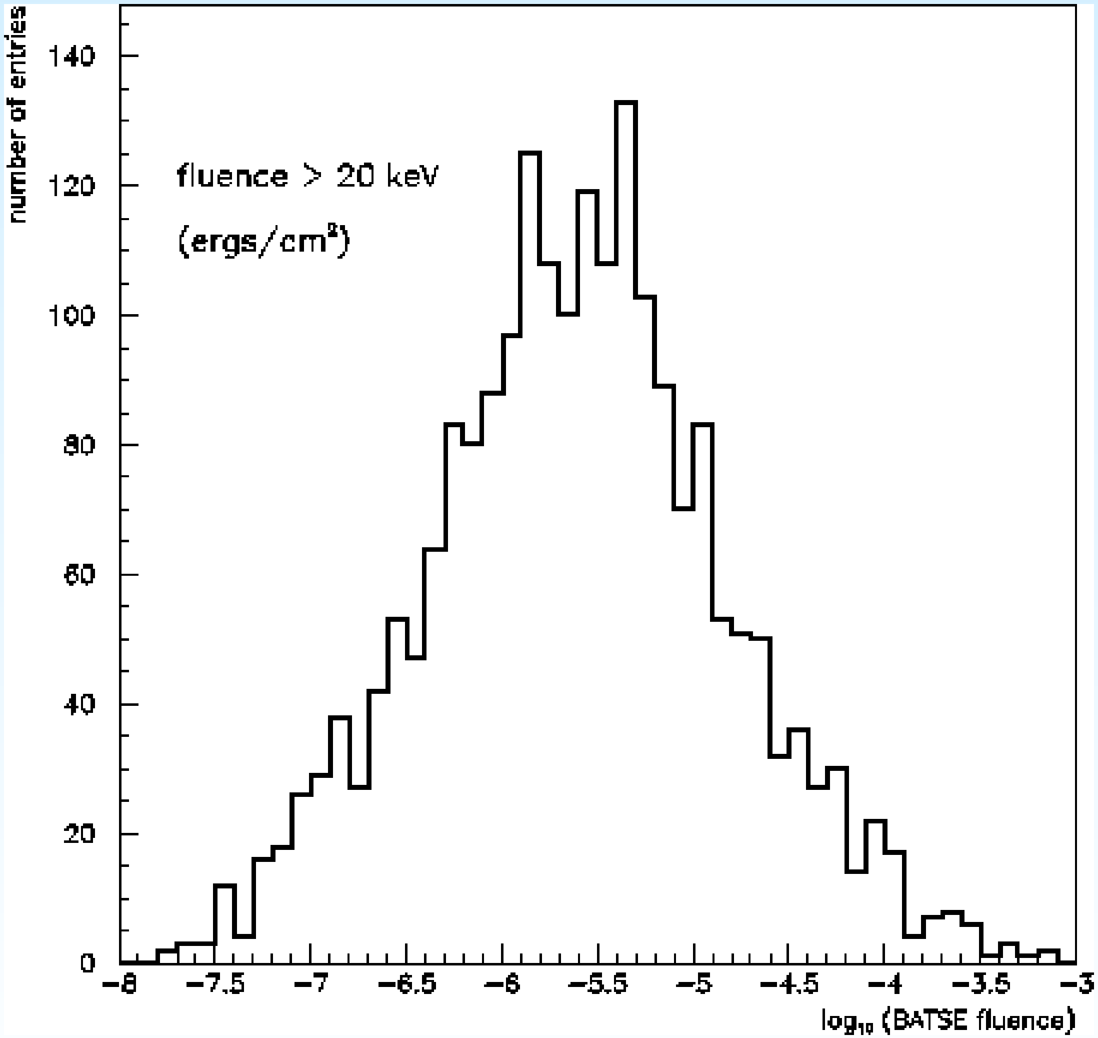
$N_\nu \approx$ 0.09 for δ = 100 and 200



t_{var} = 1 sec (if t_{var} = 0.01 sec, much stronger $\gamma\gamma$- absorption)

Fluence Distribution of GRBs

Fluence distribution of 2135 BATSE GRBs



φ

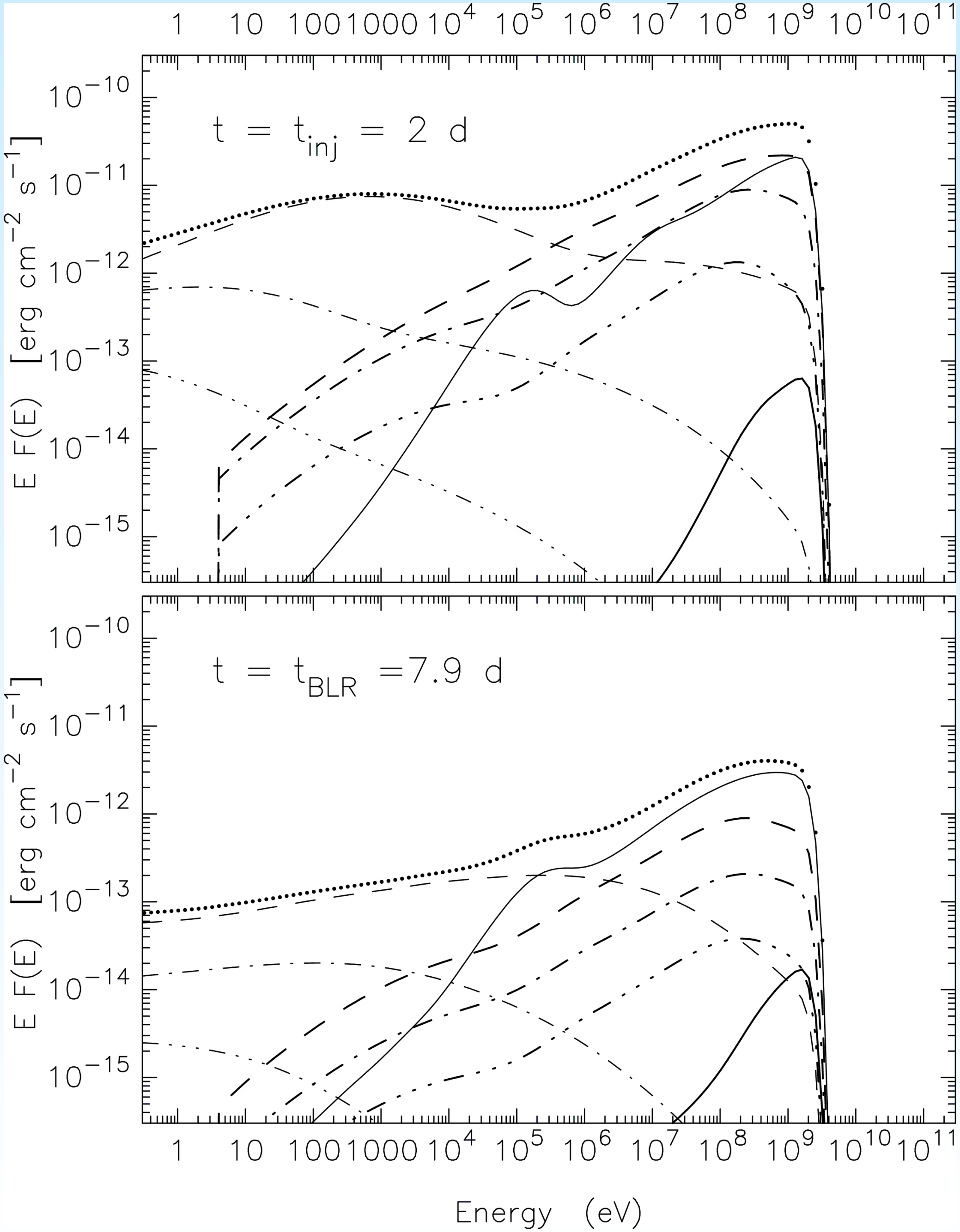
McCullough (2001)

$$N_\nu(\geq \varepsilon_\nu) \approx$$

$$\int_{\varepsilon_\nu}^{\infty} d\varepsilon_1 \frac{\nu\Phi_\nu}{\varepsilon_1^2} P_{\nu\mu} A_\nu$$

$$\approx 0.6\varphi_{-4} A_{10}$$

Detection of neutrinos requires GRBs at fluence levels > $3\text{x}10^{-4}$ ergs/cm^2 (2-5 GRBs per year at this level) ***unless GRBs are hadronically dominated***



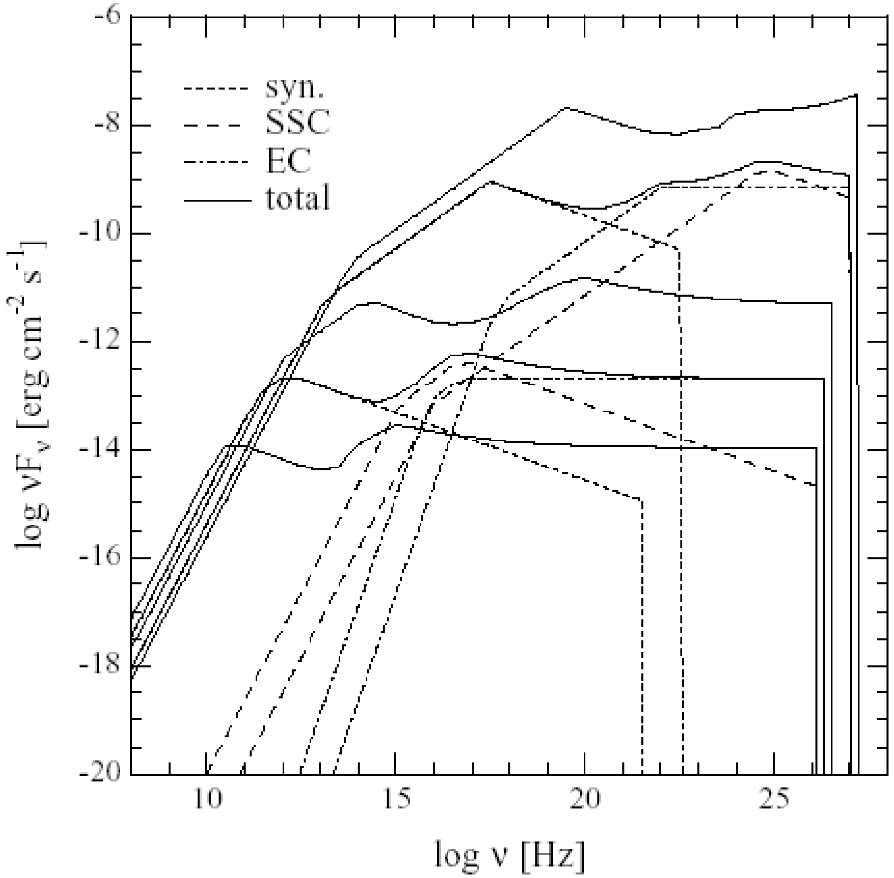
Hadronic Cascade Radiation from GRBs

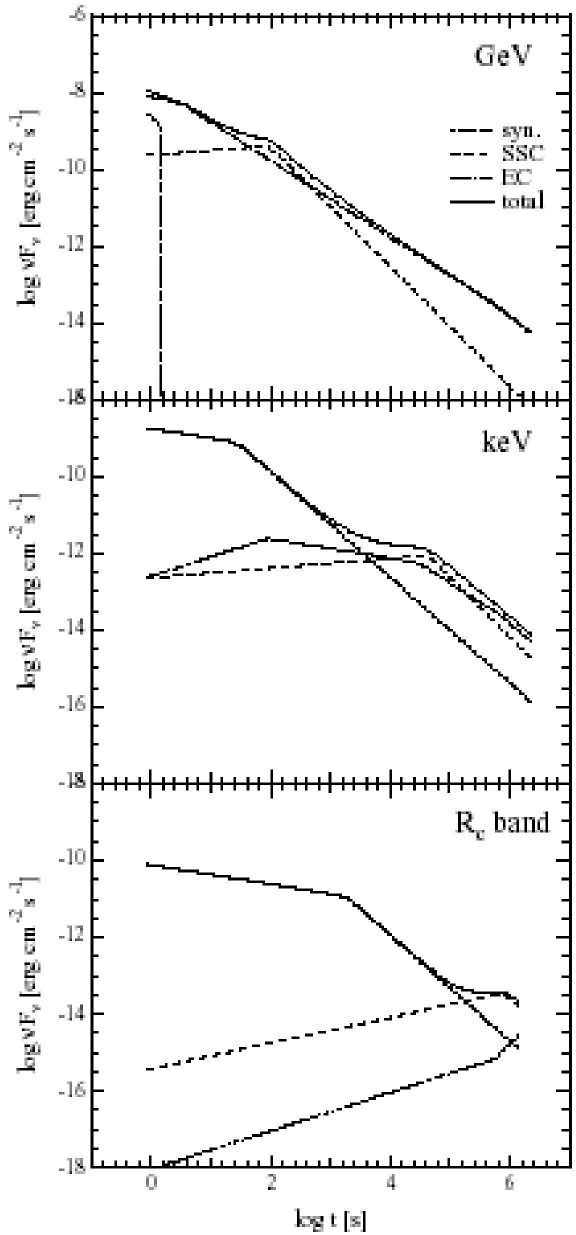
(Limits proton/electron ratio)

Hadrons produce independent spectral component in GRB emission

Presence of hadronic emission + $\gamma\gamma$ attenuation supports hadron acceleration in GRBs

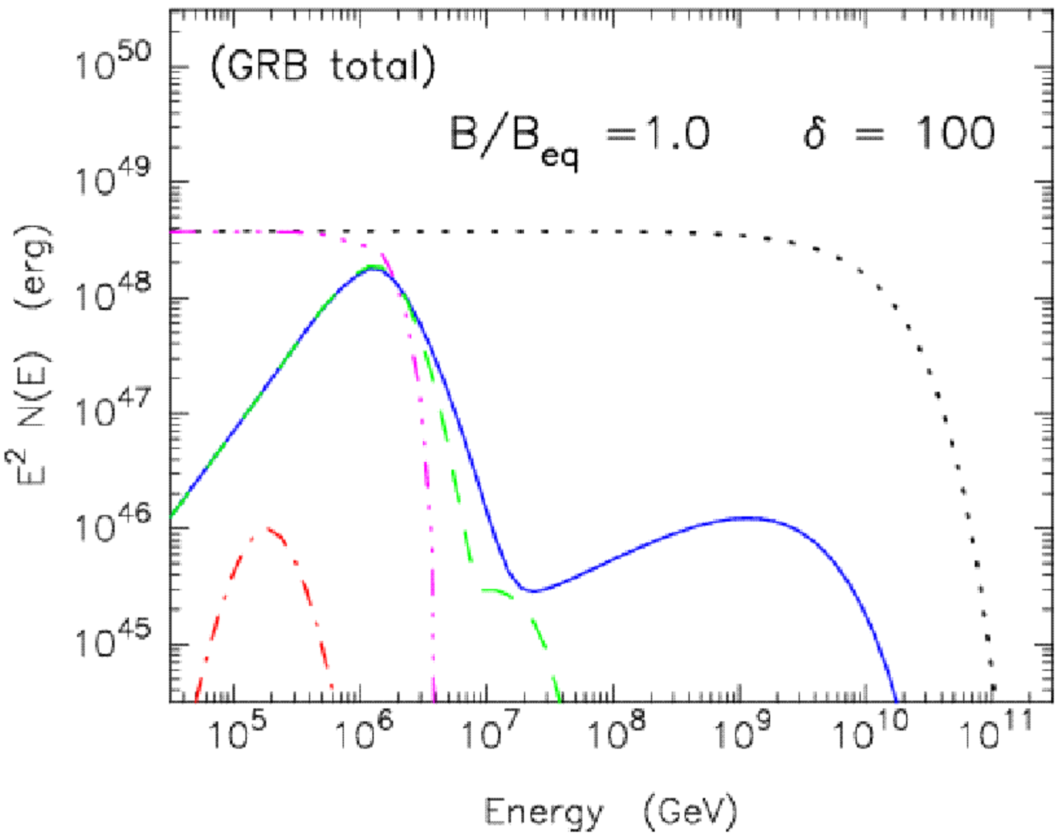
External Compton Component in Supranova Model





(Inoue et al. 2002)

Neutral Beams from GRBs



Neutral particle escape from synchrotron emission field

GeV-TeV γ-ray halo (from misaligned GRBs);

High-energy cosmic rays

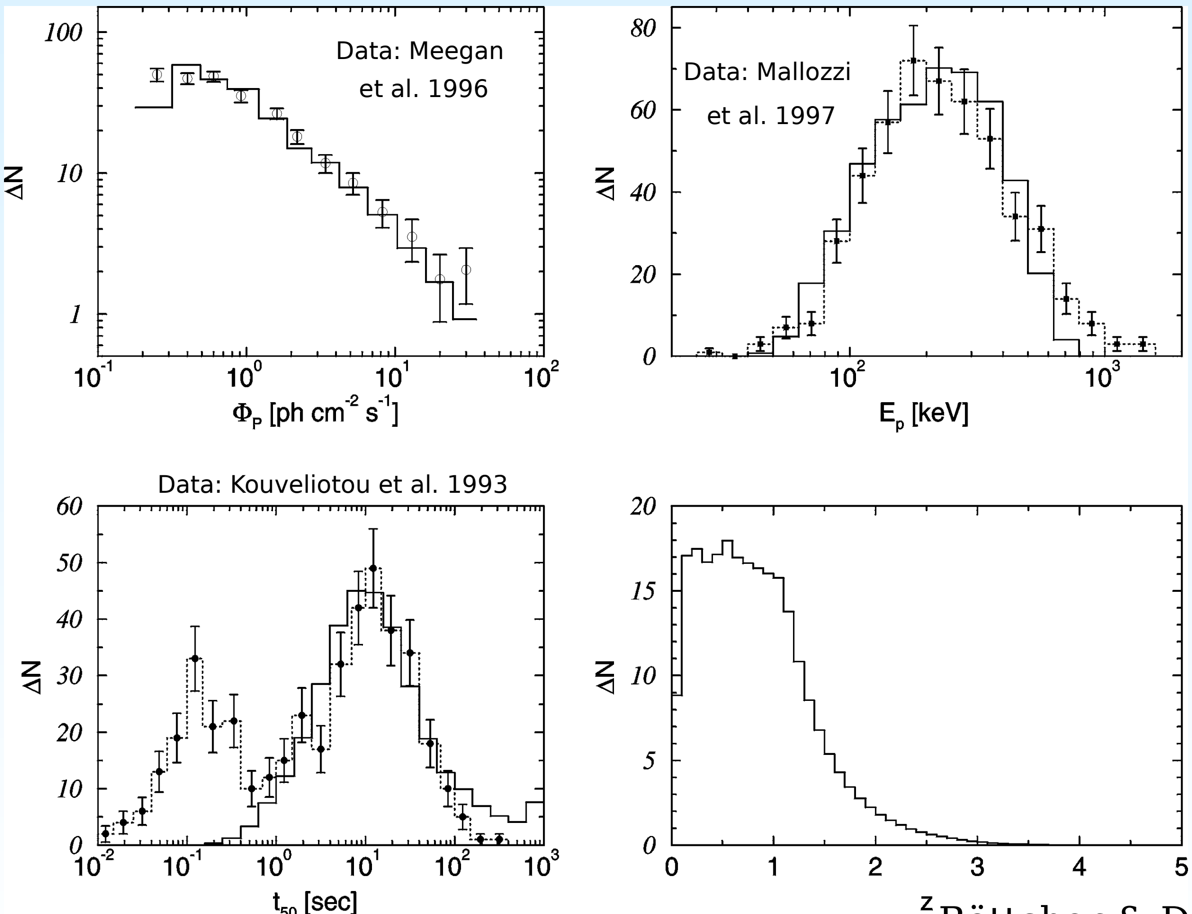
Neutron decay halos

Synchrotron and Compton Neutron-Decay Halos

- Neutrons formed through photomeson processes during cosmic ray acceleration escape from blast wave $n \rightarrow p + e^- + \nu_e$
- Decay of ultrahigh energy neutrons occurs at ~100 kpc
- Produce nonthermal synchrotron radiation, depending on strength of halo magnetic field
  - Produce nonthermal γ rays from Compton scattering of CMB
    - γ rays materialize through $\gamma\gamma \rightarrow e^+e^-$
    - form extended pair and gamma-ray halo

Cosmological Statistics of GRBs in the External Shock Model

- Assume that distribution of GRB progenitors follows star formation history of universe
- Broad distributions of baryon-loading Γ_0 and energy releases E are required. Assume power laws for these quantities.
  - $10^{-6} < E_{54} < 1$; $N(E_{54}) \propto E_{54}^{-1.52}$; $\Gamma_0 < 260$; $N(\Gamma_0) \propto \Gamma_0^{-0.25}$



Unfortunately, rather few clean fireballs

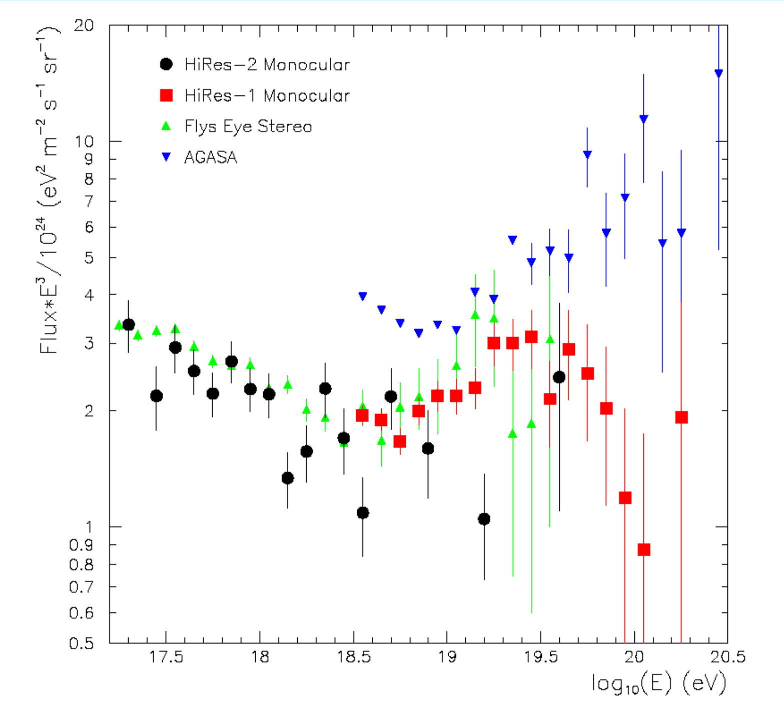
$\Rightarrow$ Energy rate density into local universe

$$\frac{dE(z=0)}{dVdt} \cong 4\times 10^{44}\frac{ergs}{Mpc^3 - yr}$$

Böttcher & Dermer (ApJ, 2000, 529, 635)

UHECRs from GRBs

- UHECRs lose energy due to photomeson processes with CMB
  - $p + \gamma \rightarrow p + \pi^0$, $n + \pi^+$
  - GZK Radius $x_{1/2}(10^{20}\ \mathrm{eV}) \cong$ 140 Mpc



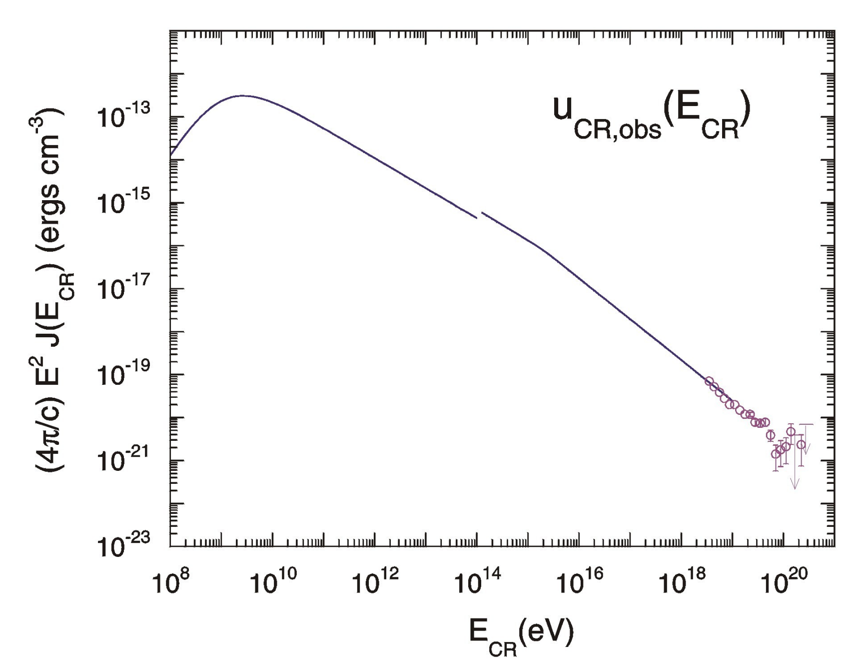
- Energy density within GZK Radius:

Stanev et al. (2000)

$$\frac{dE(z=0)}{dV} \cong \frac{dE(z=0)}{dVdt}\left(\frac{140Mpc}{c}\right)$$

$$\cong 6\times10^{21}\frac{ergs}{cm^3}$$

Vietri (1995); Waxman (1995)



Rate and Power of GRBs into Milky-Way--Type (L*) Galaxies

CD (ApJ, 2002)

- **BATSE obs. imply ~ 2 GRBs/day over the full sk**
- **Beaming factor increases that rate by factor ~500**
- **Volume of the universe ~ $4\pi(4000\ \mathrm{Mpc})^3/3$**
- **Density of L* galaxies ~ $1/(200\text{-}500\ \mathrm{Mpc}^3)$**

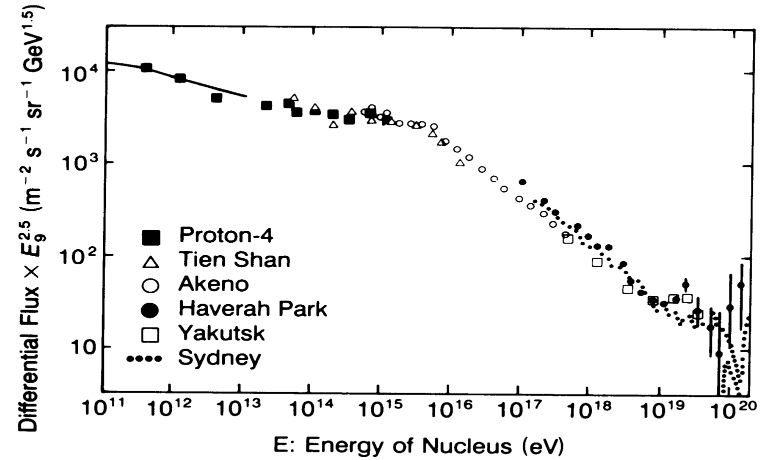


Figure 2. Cosmic ray energy spectrum multiplied by $E^{2.5}$ to better show the spectral variations. (*Adapted from Hillas, 1984.*)

Rate per L* galaxy

$$\approx \frac{500\,Mpc^3/L^*}{\frac{4\pi}{3}(4000\,Mpc)^3}\,\frac{1}{day}\,\frac{365}{yr}\times 1000 f_3 \times SFR \times K_{FT}$$

$$\approx \left(\frac{SFR}{1/6}\right)\times\left(\frac{K_{FT}}{3}\right)\frac{f_3}{3.5\times 10^4\,yr} \approx f_3/(3000\,yrs)$$

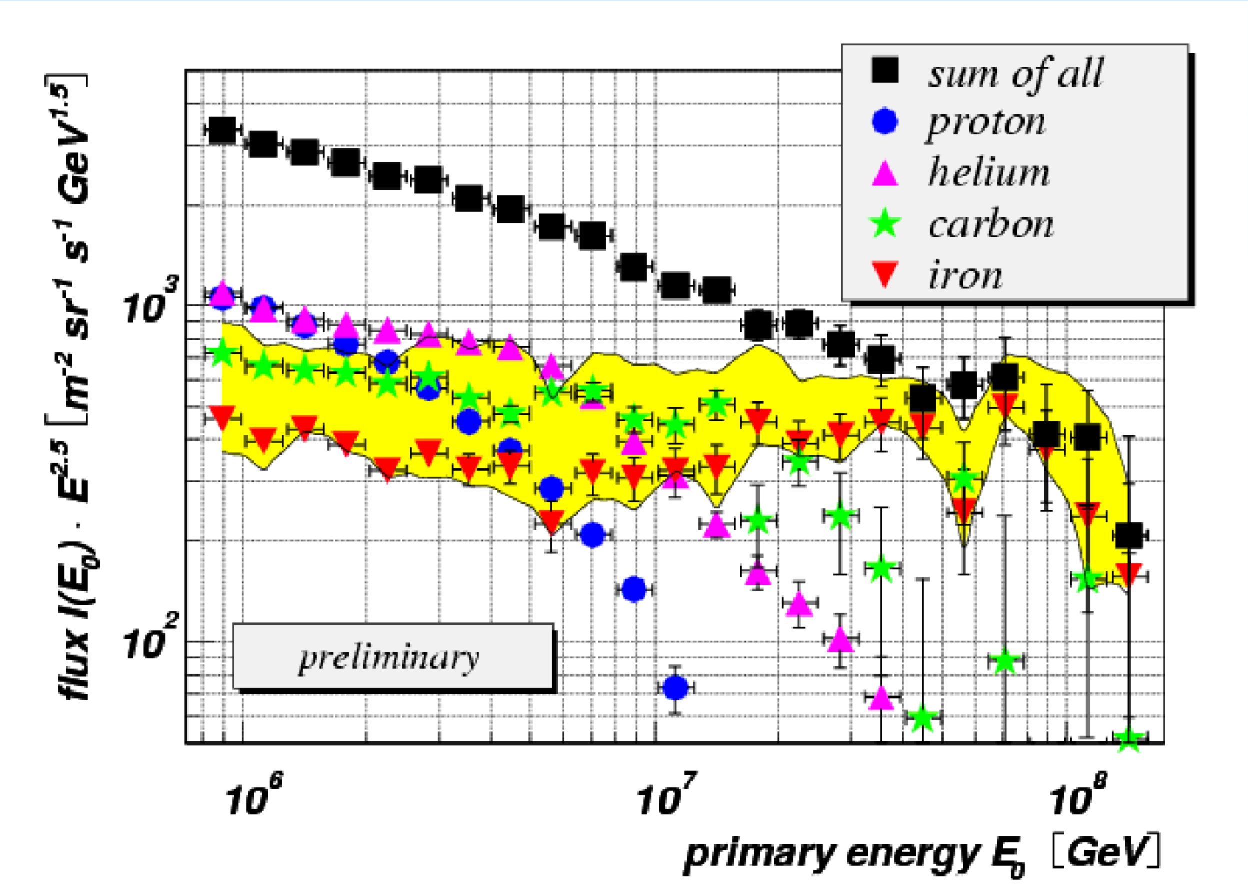
Time-averaged power per L* galaxy

$$\approx \left(\frac{SFR}{1/6}\right)\times\left(\frac{K_{FT}}{3}\right)\times\frac{1.5\times 10^{51}\,ergs}{2600\,yrs \times 3\times 10^7}$$

$$\approx 2\times 10^{40}\left(\frac{SFR}{1/6}\right)\left(\frac{K_{FT}}{3}\right) ergs\,s^{-1};\ \eta_\gamma = 1/3$$

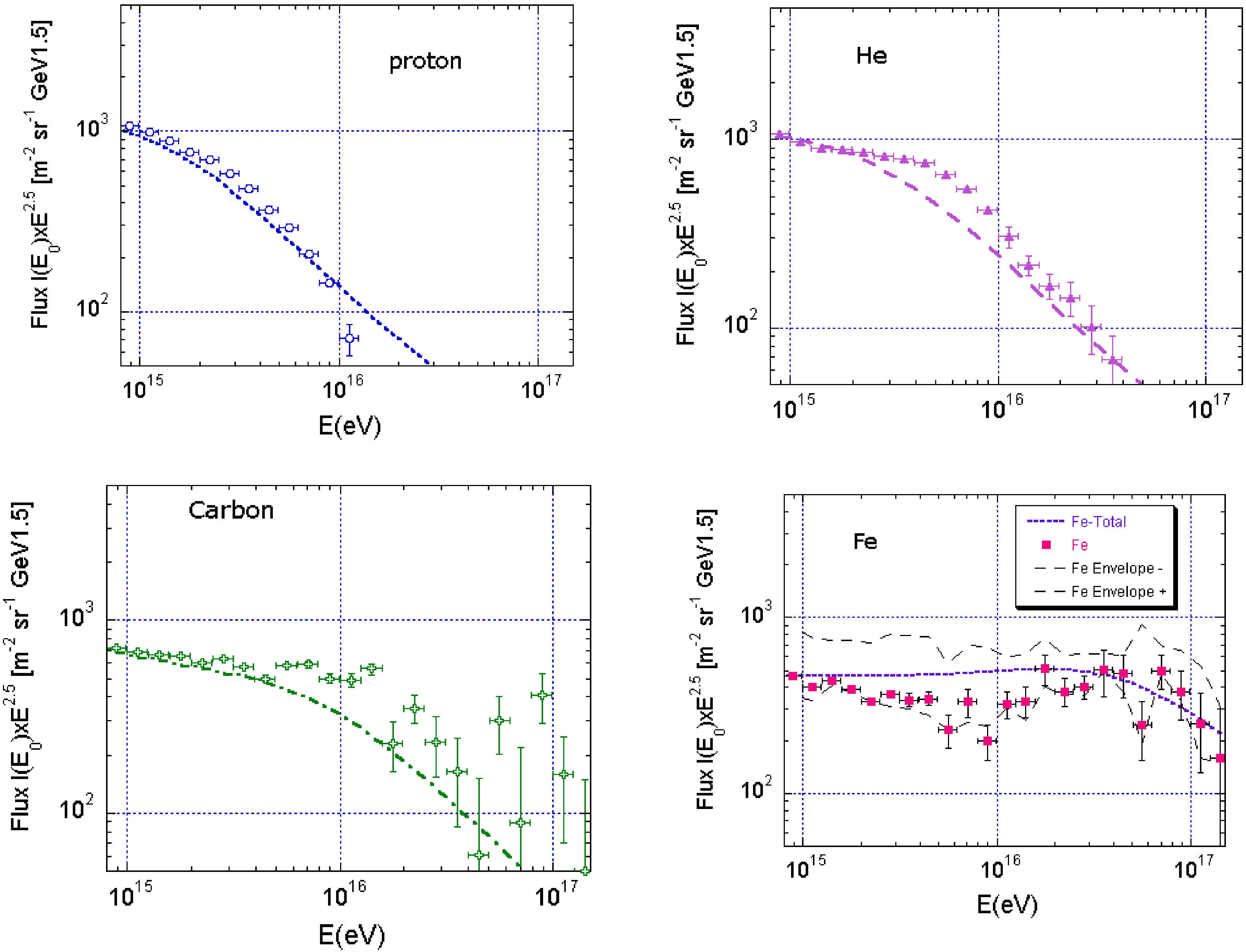
K_{FT} correction factor for clean and dirty fireballs

KASCADE Results on Knee Composition



Model with Cosmic Ray
Injection from GRBs

Break from Propagation Effects due to diffusion by scattering off MHD turbulence in galactic disk and halo


proton
He
Carbon
Fe
Fe-Total
Fe
Fe Envelope -
Fe Envelope +
Flux I(E0)xE2.5 [m-2 sr-1 GeV1.5]
E(eV)
10^3
10^2
10^15
10^16
10^17

Gamma Rays and Neutrinos from GRBs

Gamma-rays + Neutrinos: test collapsar and supranova models
Neutrinos ⇒ Cosmic Ray Sources
Gamma-rays: Sites of cosmic ray acceleration in Galaxy

Prompt and Afterglow Emission

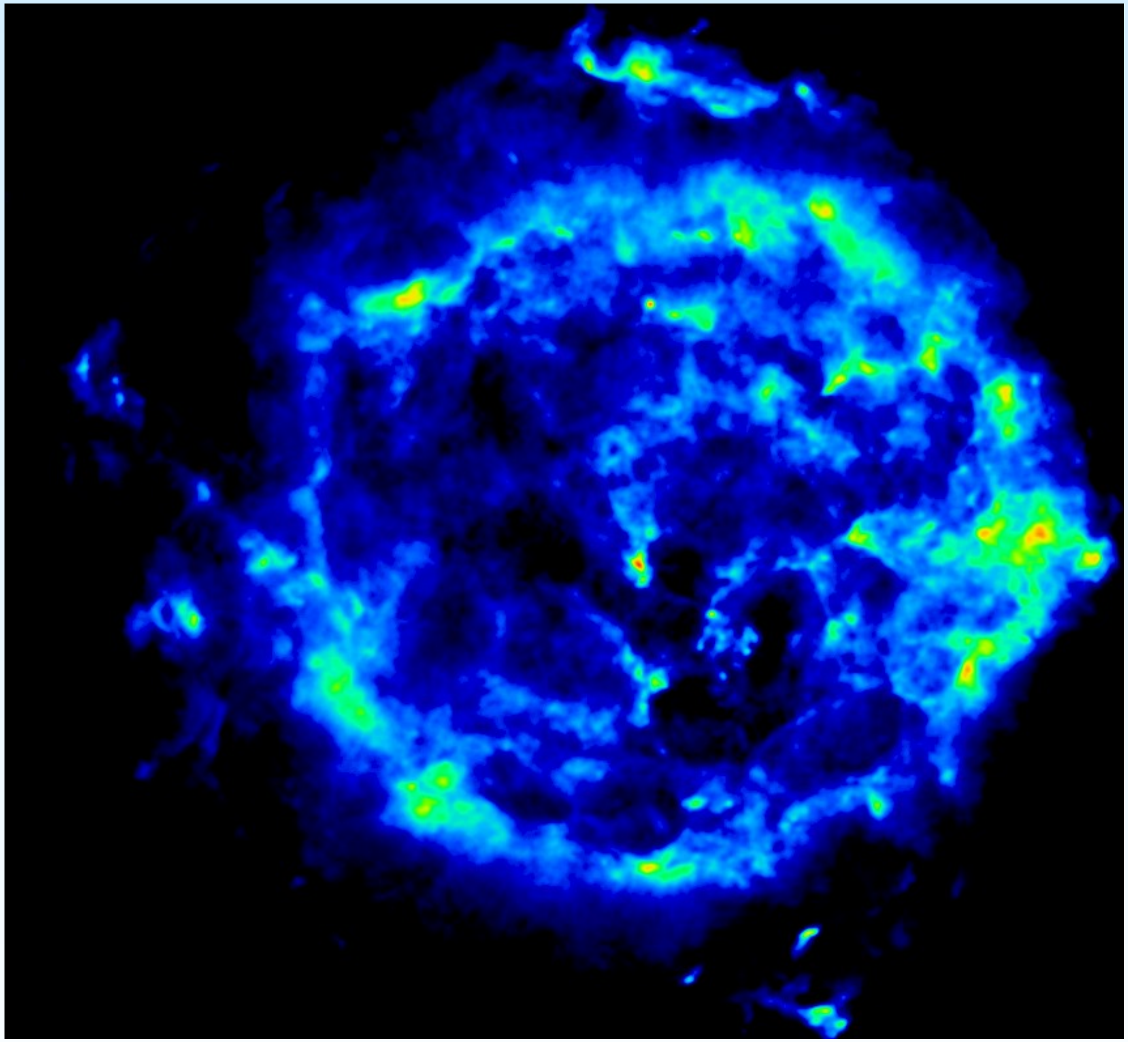
- **SSC**
- **ERC component**
- **Hadronic Cascade Radiation**
- **Secondary Nuclear Production from Interactions with Shell Material**

Cosmic Ray Production from GRBs

- **Neutron-Decay Radiation; Gamma-ray halo emission**
- **Hadronic Emission from Cosmic Rays formed by SN**

Cosmic Rays originate from the stars that produce the subclass of SNe that makes GRBs
Survey galaxy at TeV energies to find bright cosmic ray supernova

Highly Structured SN Remnant Ejecta



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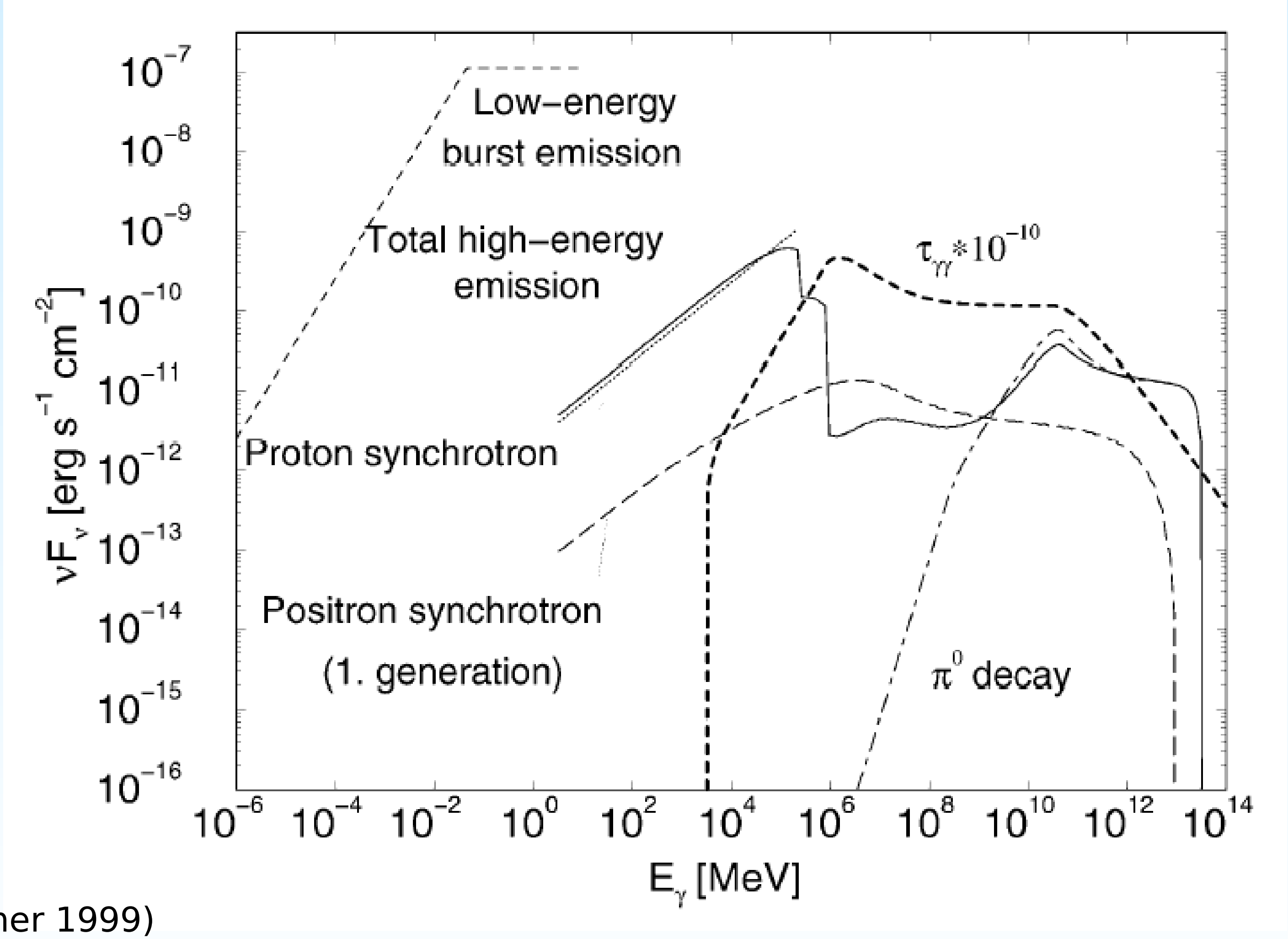
Energetic Hadron Component in GRB Blast Waves

Requires proton acceleration to high energies

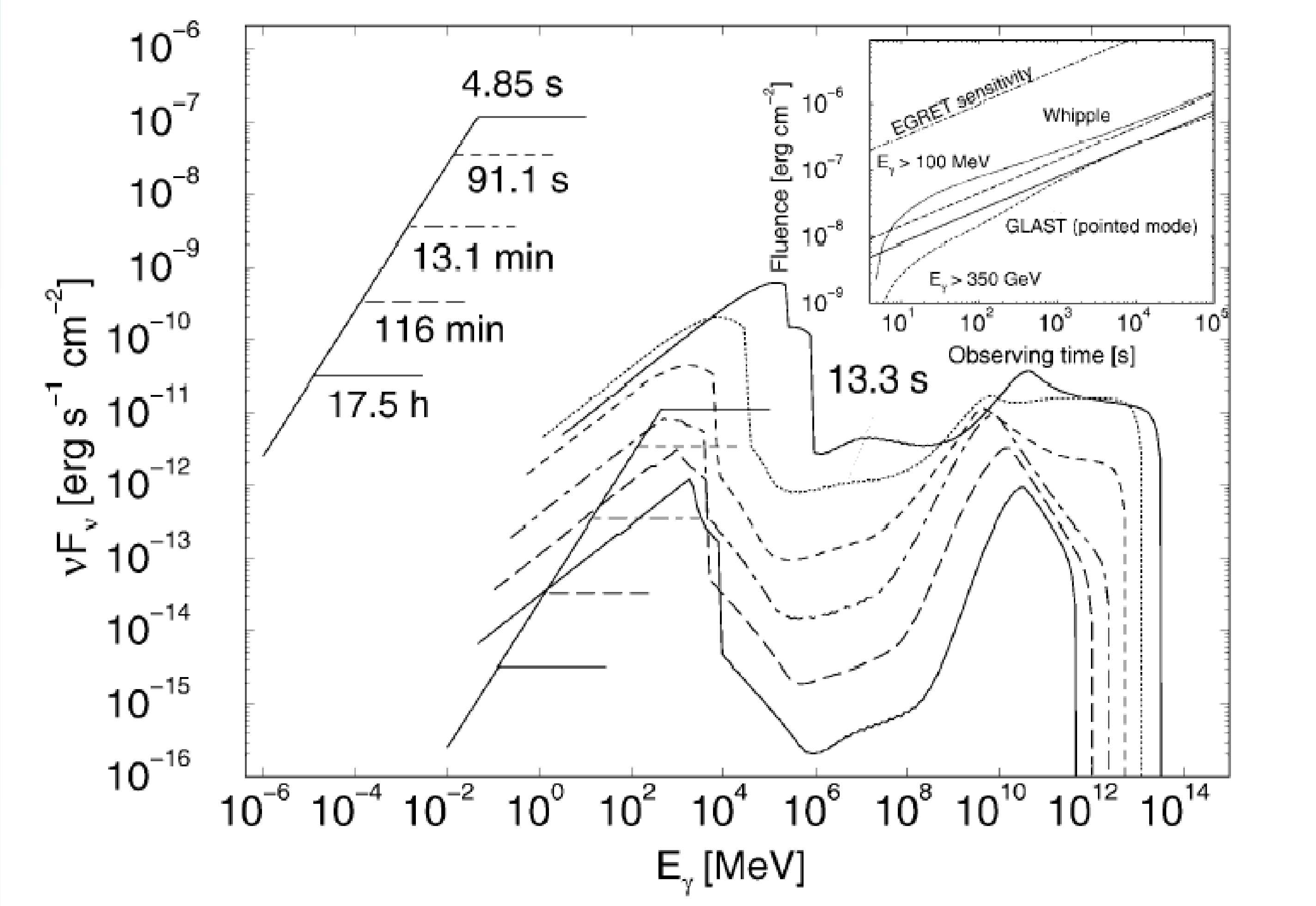
Proton synchrotron component observed with GLAST



(Böttcher and Dermer 1999)

Proton Synchrotron Emission

Slow decay of proton emission



How to Resolve Quandary?

Constant energy reservoir result: favors uniform source type

X-ray features favor delayed two-step collapse process

Delayed red bumps favor SN at about the same time as GRB (within a few days).

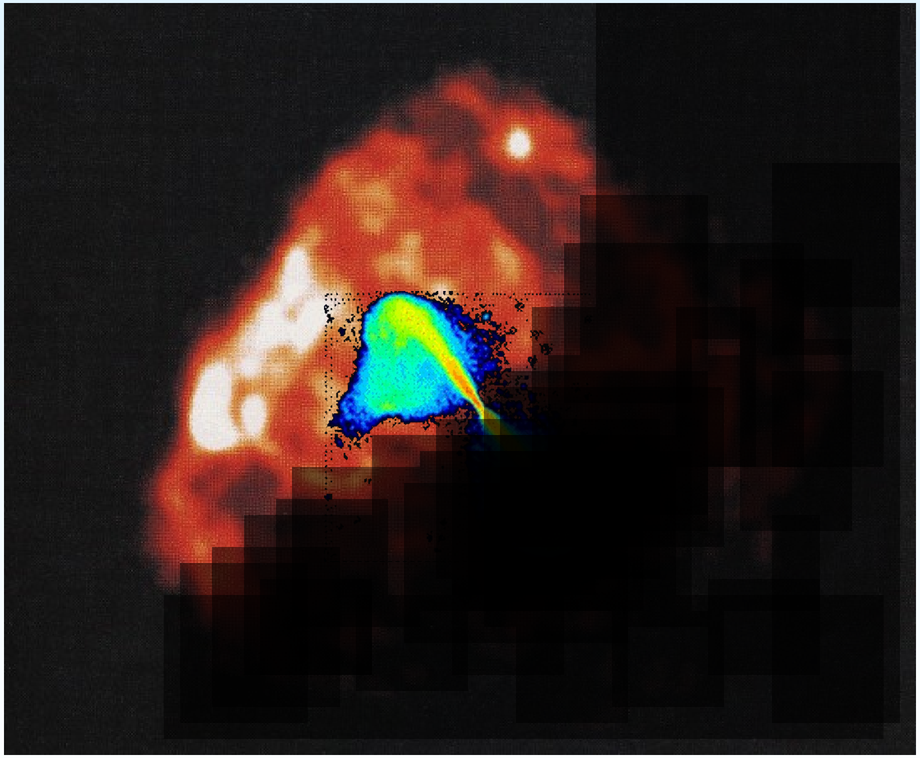
Shock interacting with WR progenitor stellar wind (Ramirez-Ruiz et al. 2001)– requires 4 free parameters;

Heating of SNR shell by pulsar wind synchrotron nebula (CD 2002)

Supranova model

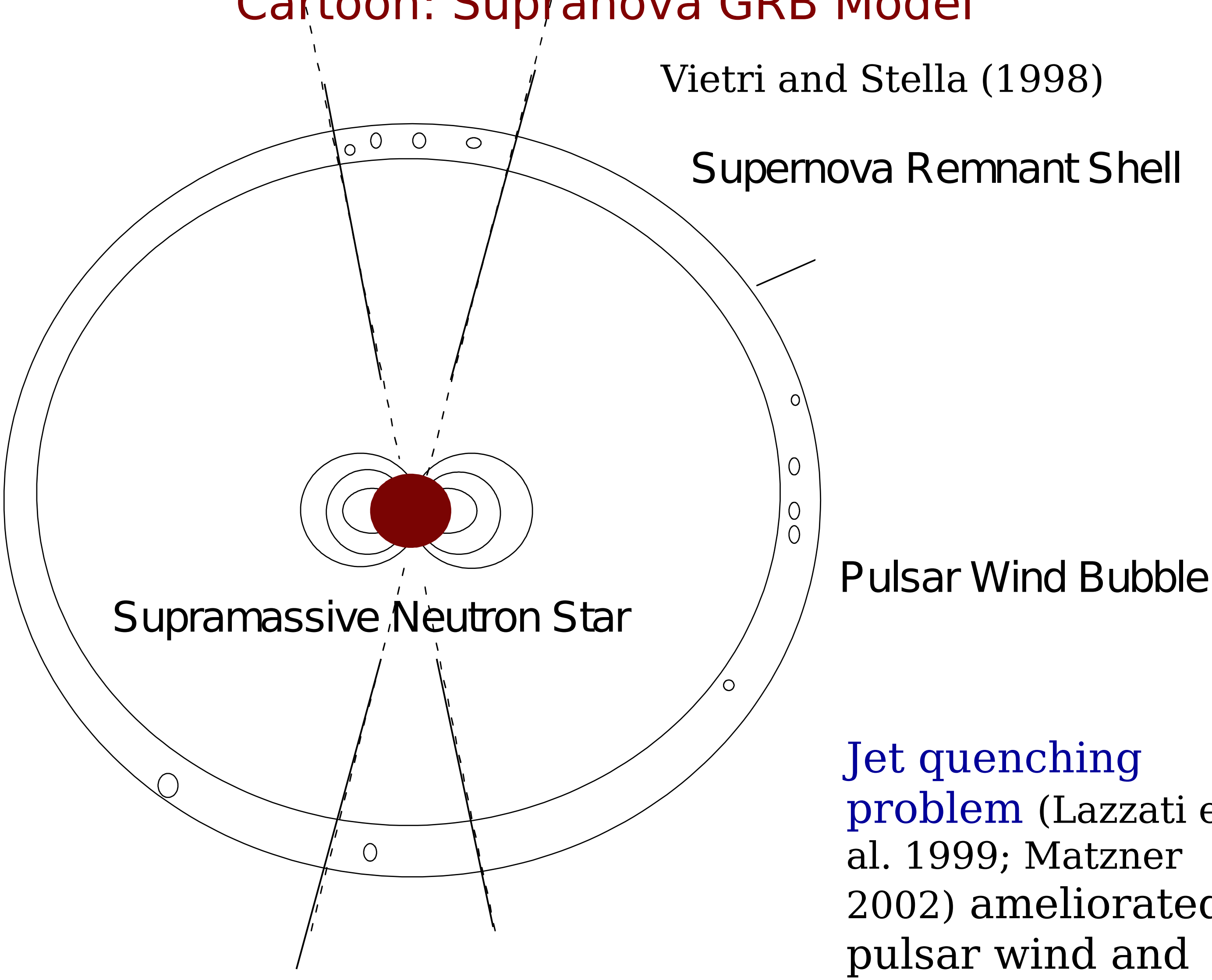
- Supranova model (Vietri and Stella 1999)
  - Two-step collapse to black hole
  - Super-Chandresekhar mass neutron star stabilized against prompt collapse by rotation
  - Supernova shell of enriched material
  - In dusty, star-forming regions
  - Prompt collapse following days-years spin-down episode

  Supranova model more easily explains Iron absorption and fluorescence line observations
  - Formation of pulsar wind and plerion (Königl and Granot 2002)
  - Blast wave physics in highly magnetized and enriched pair enviroment
  - Source of external radiation (Inoue, Guetta, and Pacini 2003; Guetta and Granot 2003)



Cartoon: Supranova GRB Model

Vietri and Stella (1998)



Jet quenching problem (Lazzati et al. 1999; Matzner 2002) ameliorated by pulsar wind and anisotropic SN ejecta

UHECRs from GRBs

Waxman (1995); Vietri (1995)

- Typical fluence and rate of BATSE GRBs:
  - $F_\gamma \approx 10^{-6}$ ergs cm^{-2} ; $N_{GRB} \approx 2$/day
- If weakest GRBs at z ~ 1, then d ≅ 10^{28} cm
  - $E_\gamma \approx 4\pi d^2 F_\gamma \approx 10^{51}$ ergs ≈ E_{UHECR}
- UHECRs lose energy due to photomeson processes with CMB
  - $p + \gamma \rightarrow p + \pi^0$, $n + \pi^+$
  - GZK Radius $x_{1/2}$ (10^{20} eV) ≅ 140 Mpc
- Energy density within GZK Radius:
  - $u_{UHECR} \cong \varepsilon_{GRB}\,(x_{1/2}/c) \cong$
  - E_{GRB} (140 Mpc/c) ≅ 10^{-22} ergs/cm^3

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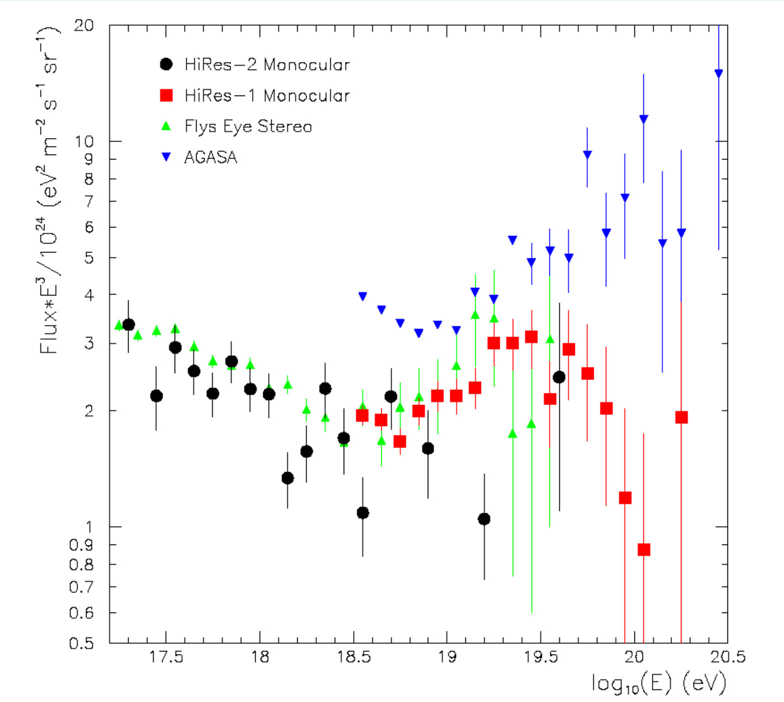

Stanev et al. (2000)

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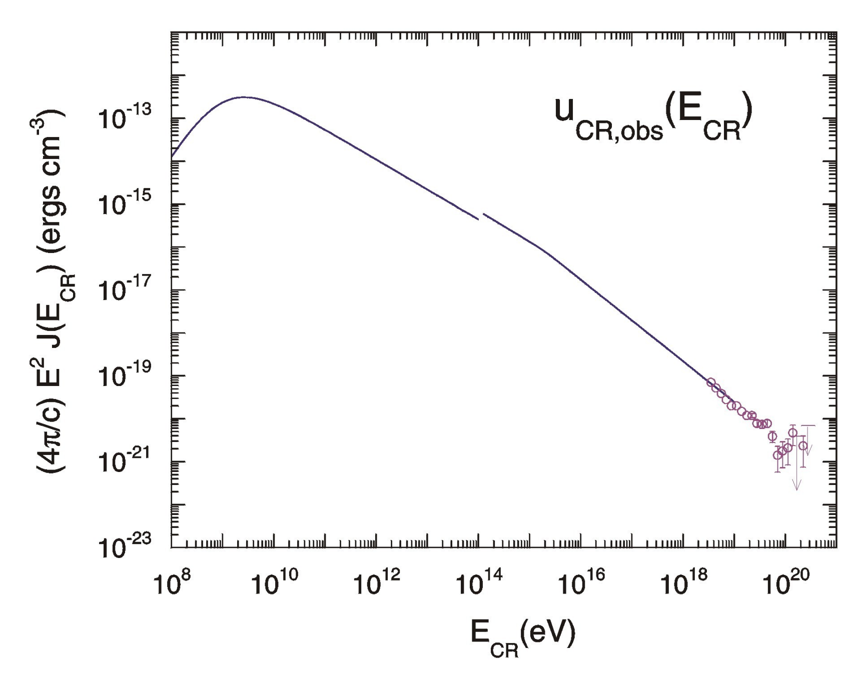
$$\overline{}$$
$$0.5\ \text{day}\times(4\pi/3)(10^{28}\text{cm})^3$$

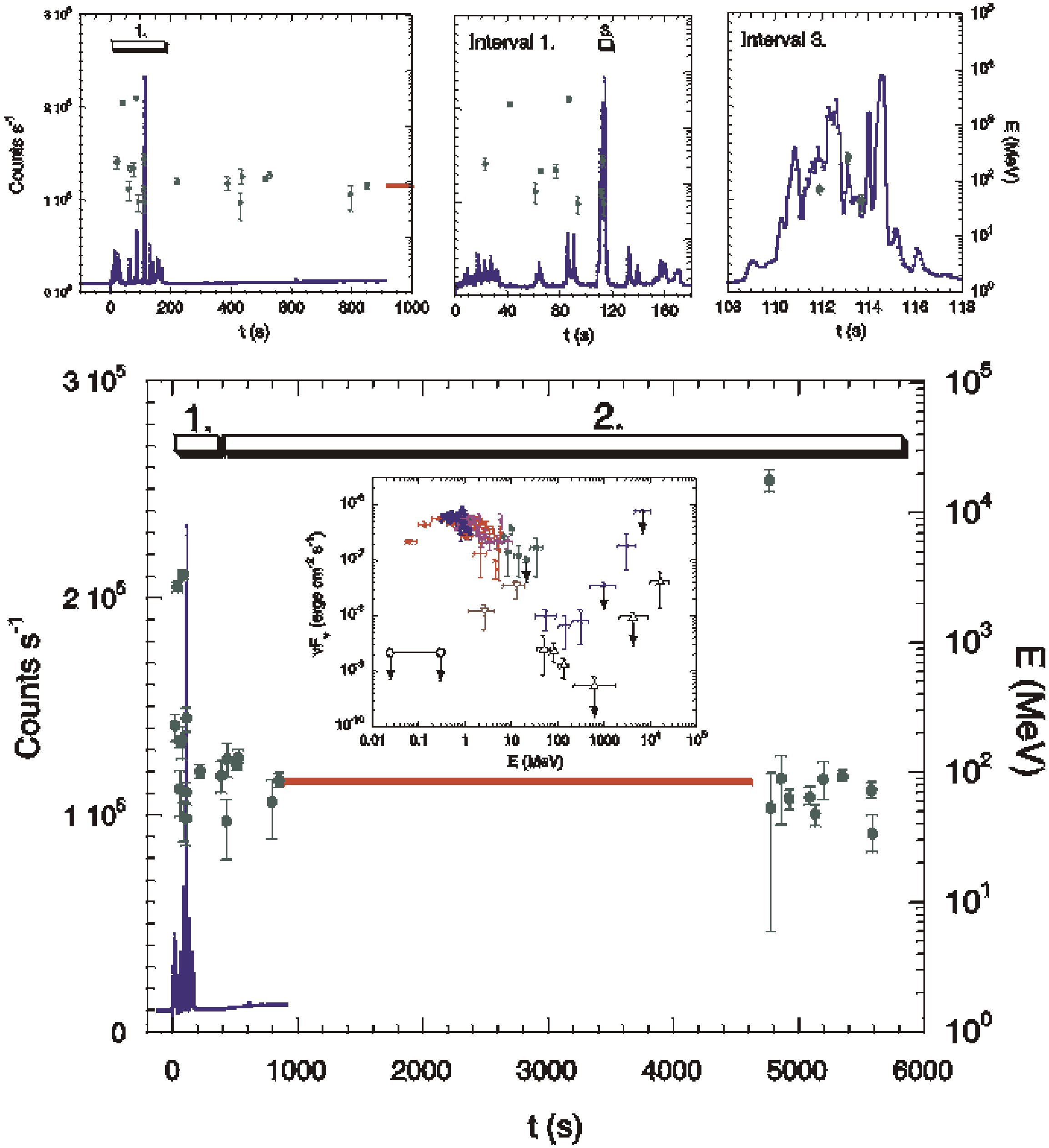


GRB 940217

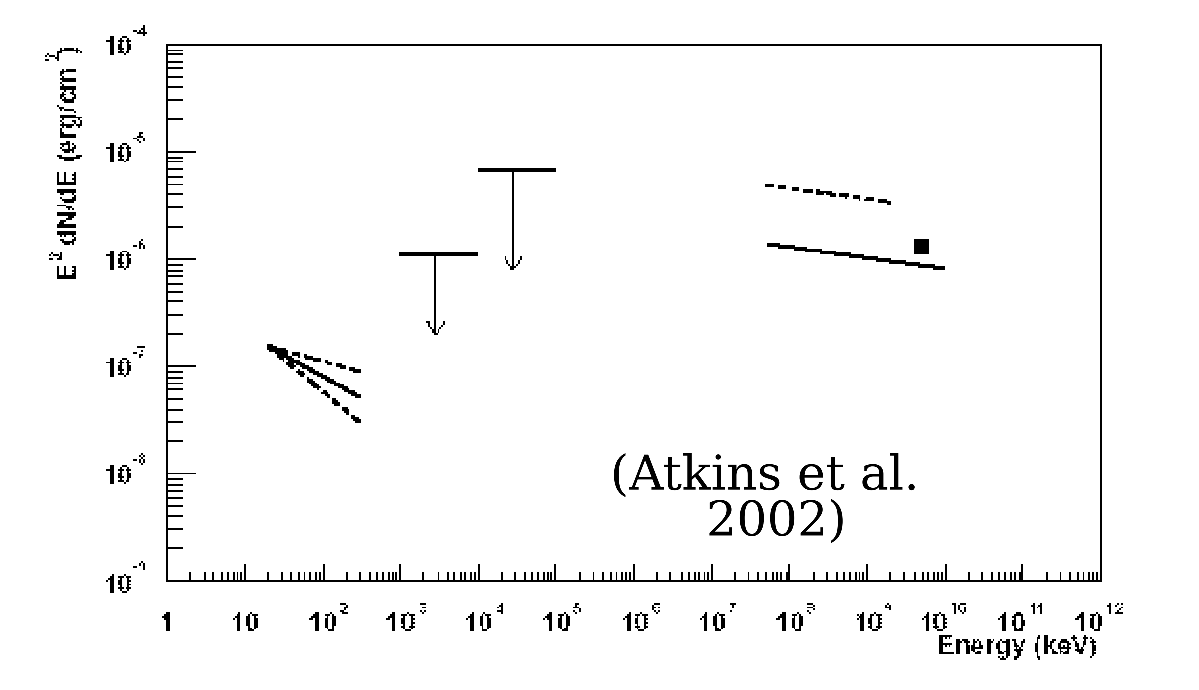
⇒ **Nonthermal processes**

Origin of hard radiation?

1. Synchrotron
2. SSC
3. External Compton Scattering
4. Hadronic Emission (proton synchrotron/ photomeson/ secondary nuclear production)



GRB 970417a TeV Detection with Milagrito



(Requires low-redshift GRB to avoid attenuation by diffuse IR background)

Other evidence for high-energy radiation from GRBs:

Seven GRBs detected with EGRET either during prompt sub-MeV burst emission or after sub-MeV emission has decayed away (Dingus et al. 1998)

Average spectrum of 4 GRBs detected over 200 s time interval from start of BATSE emission with photon index 1.95 ($\pm$0.25) (> 30 MeV)

EGRET/TASC observations of GRBs

Nonthermal γ-Ray Emission: $\gamma\gamma$ Transparency Argument for Bulk Relativistic Motion

In comoving frame, avoiding threshold condition for $\gamma\gamma$ interactions requires

$$\epsilon_1' < 1 \Rightarrow \delta > 200(1+z)E(100MeV)$$

Requirement that $\gamma\gamma$ optical depth be small:

$$\tau_{\gamma\gamma} \approx \frac{\sigma_T}{3}\left(\frac{2}{\epsilon_1'}\right)n'_{ph}\left(\frac{2}{\epsilon_1'}\right)r_b\ ,\ r_b \le \frac{ct_v\delta}{(1+z)}$$

$$\delta > 200[(1+z)d_{28}]^{1/3}\left[\frac{f_{-6}\,E_2(GeV)}{t_v(s)}\right]^{1/6}$$